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Biomass and Nutrient Content of a 41-Year-Old Loblolly Pine (Pinus taeda *L.) Plantation on a Poor Site in South Carolina*

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DAVID H. VAN LEAR
JACK B. WAIDE
MICHAEL J. TEUKE

ABSTRACT. Biomass and nutrient content regression equations were developed from analyses of 16 loblolly pine trees growing in a 41-year-old plantation on a poor site in the upper Piedmont of South Carolina. Above-stump biomass of the stand, which had been thinned twice, averaged 109.6 t/ha. Nutrient concentrations were highest in the foliage and lowest in the wood. Nutrient content ranged from 10.4 kg/ha for P to 123.2 kg/ha for N. Crown components, with only 20 percent of the above-stump biomass, contained 49 percent of the N, 45 percent of the P, 37 percent of the K, and 36 percent of the Ca. Predictions of stand nutrient content were similar regardless of whether estimated by regression equations relating nutrient content of tree components to dbh or by multiplying predicted total biomass of each component by its average weighted nutrient concentration. Nutrient contents of other nearly mature loblolly pine plantations could be estimated by determining average weighted nutrient concentrations of biomass components by sampling a small number of trees and multiplying these values by stand dry weight as predicted from the presented biomass equations. FOREST SCI. 30:395–404.

ADDITIONAL KEY WORDS. Whole-tree harvest, nutrient cycling.

LOBLOLLY PINE (*Pinus taeda* L.) is the major commercial tree species in the southern United States, and management systems for the regeneration and culture of this species are among the most intensive used in any forest type. In recent years, much concern has been expressed, as evidenced by recent symposia at Mississippi State University (Tippin 1978) and at State University of New York (Leaf 1979), about the effects of intensive silvicultural practices such as short rotations, whole tree harvesting, and types of site preparation on the nutrient status and productivity of forest sites.

Two different approaches have been used to predict the impacts of management on long-term productivity of loblolly pine. First is the balance sheet approach used by Switzer and Nelson (1973) and Wells and Jorgensen (1975), while the second involves the use of systems analyses and computer simulation (Swank and Waide 1980). In either of these approaches, it is necessary to estimate the biomass and nutrient content of the vegetative pool before budgets or models can be developed. Accurate prediction of the nutrient capital of a forest stand depends in large part on the accuracy of biomass prediction. The use of regression equations to predict biomass of tree components from tree diameter is preferable to using

The authors are, respectively, Professor, Department of Forestry; Research Ecologist, Zoology Department; and graduate student, Department of Forestry, Clemson University, Clemson, SC 29631.
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an average tree approach since the proportions of foliage, branches, bark, and wood change with tree size (Jokela and others 1981). However, there appears to be no standard method for estimating nutrient content of a stand, even though the various methods probably produce different results (Auchmoody and Greweling 1979).

The objective of this study was to develop biomass and nutrient content equations for loblolly pine trees growing in a 41-year-old plantation in the upper Piedmont of South Carolina, and to use these equations to estimate biomass and nutrient content of the stand.

Study Area

A 41-year-old loblolly pine plantation occupying 12.4 ha on the Clemson Experimental Forest was selected as the study area. The stand was originally planted at 2 × 2 m spacing and had been thinned twice, once at age 22 years and again at age 30 years. Average dbh was 25.5 cm, and average height of dominant and codominant trees was 23.2 m. Basal area of the pine overstory averaged 18.5 m^2/ha with an average density of 437 stems/ha. Occasional yellow-poplar (*Liriodendron tulipifera* L.) and oaks (*Quercus* spp.) occurred in the overstory. Associated understory species consisted of seedlings and saplings of the above species, as well as black cherry (*Prunus serotina* Edrh.), eastern redcedar (*Juniperus virginiana* L.), hickory (*Carya* spp.), red maple (*Acer rubrum* L.), blackgum (*Nyssa sylvatica* Marsh.), sourwood (*Oxydendrum arboreum* L.), and numerous herbaceous species.

The plantation was established in 1939 on an eroded phase of the Pacolet fine sandy loam, a clayey, kaolinitic, thermic Typic Hapludult, in the upper Piedmont of South Carolina. Slopes average about 13 percent, with numerous ephemeral stream channels present which developed when the land was in agriculture.

Pacolet soils have a surface layer of brown sandy loam underlain by red, firm clay loam and clay. Developed from granitic and gneissic materials, they are well drained. Much of the surface soil was lost during decades of row farming, but erosion was greatly reduced after a forest floor of pine needles developed. Annual precipitation averages 130 cm and is well distributed throughout the year. Maximum and minimum yearly temperatures are 22°C and 9°C, respectively, with a mean annual temperature of 16°C.

Methods

Sixteen sample trees ranging from 12.7 to 38.6 cm at diameter breast height (1.4 m) were felled at 15 cm above ground line during February and early March of 1979 (Table 1). These trees were selected as representative of typical trees in each of the four crown classes in the stand. Total height and height to a 5 cm top were measured on each felled tree. Branches were cut from the bole, which was then cut into four sections of equal length, based on the distance from the bottom to the 5 cm top. Discs, five in all, were cut from the base of each section and from the top of the smallest section. Green weights of the bole sections and discs were determined in the field, as was that of the foliage, which was completely removed from each tree. Branches were separated into three diameter-size categories, i.e., <1, 1–5, and >5 cm, weighed green, and a subsample bagged for transport to the laboratory. Bark was separated from the discs but not from the branch samples. All samples were stored in plastic bags at 0°C until they could be weighed after drying to a constant weight at 80°C.

Ovendry weights of bole wood and bark above the stump were calculated from moisture content and ratios of wood:bark for the discs. Calculations of ovendry weight of foliage and branches were made after their moisture content was de-

TABLE 1. Characteristics of 16 trees sampled for allometric analysis from a managed 41-year-old loblolly pine plantation in the upper Piedmont of South Carolina.

Diameter and crown class (cm)	Number of trees sampled	Dbh (cm)	Total height (m)	Above-stump biomass (kg)
<18	3	14.1 ± 0.8[a]	16.1 ± .4	62.9 ± 8.5
Suppressed		(12.7–15.5)[b]	(15.6–16.8)	(48.9–78.3)
18–27	6	22.6 ± 1.1	19.7 ± .8	204.5 ± 24.0
Intermediate		(18.8–26.9)	(17.4–22.8)	(128.6–278.8)
27–36	5	30.8 ± 1.3	22.5 ± 0.5	460.3 ± 39.4
Codominant		(27.4–34.0)	(21.1–23.5)	(349.7–588.9)
>36	2	38.2 ± .4	24.8 ± .6	855.1 ± 43.8
Dominant		(37.8–38.6)	(24.3–25.4)	(811.3–898.9)

[a] Mean ± stand error.
[b] Range of values for trees sampled in this size class.

termined. Samples of branches, bole wood, and bole bark were chipped and then ground through a Wiley mill to pass a 20 mesh screen. Foliage was similarly prepared but without chipping.

Nitrogen in the samples was determined on a Kjeldahl digest, while total P, Ca, and K were determined on a perchloric acid digest. Analyses were conducted by A & L Agricultural Laboratories, Inc. in Memphis, Tennessee.

Regression equations relating biomass and nutrient content of each tree component to dbh were developed. Data from the 16 sample trees were fit to the model:

$$\text{Log}_{10}Y = a + b \log_{10}\text{dbh}$$

where Y is the biomass or nutrient content of the tree component in kg and dbh is the diameter at breast height in cm. All biomass equations and values are expressed on an above-stump basis.

Within this 12.4 ha stand are four small watersheds with a total area of 4.94 ha. Diameters of all loblolly pine >7.5 cm dbh were measured on these watersheds. Above-stump loblolly pine biomass and nutrient content in tree components were estimated by applying the developed regression equations to the measured diameters of all trees on the four watersheds. Stand nutrient content was also calculated by multiplying total biomass of each tree component as estimated by regression equations by its weighted nutrient concentration for comparison purposes. Weighted nutrient concentrations were determined by summing the products of the concentration of each segment of a tree component and its corresponding biomass and dividing by the total biomass of that component.

Results and Discussion

Tree Biomass.—Stem biomass to a 5 cm top accounted for about 86 percent of the above-stump biomass (Table 2). Trees in the intermediate and suppressed crown classes had a larger proportion of their above-stump in stems than trees in codominant and dominant crown classes because trees in the latter crown classes had relatively greater branch biomass. Bark consistently declined as a percent of above-stump biomass progressing from the smaller to the larger diameter trees. Foliage from these trees, which were sampled during January and February, averaged 2.5 percent of above-stump biomass. The low percentage of foliage is

TABLE 2. Proportion (percent) of above-stump biomass found in components of four size classes of trees sampled from a 41-year-old loblolly pine plantation.

Tree component	Dbh class (cm) and crown class				
	<18 Suppressed	18–27 Intermediate	27–36 Codominant	>36 Dominant	All trees
Total stem to 5 cm top	87.0 ± 0.6[a]	88.1 ± 0.7	84.5 ± 1.4	78.4 ± 0.1	85.6 ± 0.9
Stem wood to 5 cm top	76.3 ± .3	78.7 ± .9	77.6 ± 1.2	72.4 ± .6	77.0 ± .7
Stem bark to 5 cm top	10.5 ± .2	9.1 ± .6	7.3 ± .3	5.8 ± .6	8.0 ± .5
Needles	3.0 ± .2	2.2 ± .2	2.6 ± .2	2.6 ± .2	2.5 ± .1
Branches	10.0 ± .6	9.7 ± .6	12.9 ± 1.3	18.6 ± .7	11.8 ± .9
Total stem to 15 cm top	—	77.5 ± 3.7	80.4 ± .9	75.2 ± .4	78.4 ± 1.2

[a] $\bar{X} \pm s_{\bar{x}}$.

attributed to the fact that the plantation is growing on a poor site and is near maturity. Also, trees were sampled during late winter when foliage biomass would be least. Younger loblolly pine stands on excellent sites may have 5 percent of above-ground biomass in foliage (Wells and others 1975). Taras and Clark (1974) found that foliage averaged 3 percent of above-stump biomass for loblolly pine in a natural stand in Alabama.

Biomass equations for estimating weights of components of loblolly pine trees from dbh are presented in Table 3. An equation for predicting stem biomass to a 15 cm top is shown, although this equation was based on data from only eight sample trees. Nevertheless, this equation did have a high r^2 and yielded reasonable estimates of stem biomass to this diameter. The difference between stem biomass to a 5 cm top and stem biomass to a 15 cm top represents that portion of the stem that would be left in the woods after conventional harvesting of pine sawtimber. Biomass of wood and bark for the stem between a 15 and 5 cm top was calculated from ratios of wood to bark in the two discs taken from the upper stem section of sample trees. About 91 percent of the stem in this section was wood and 9 percent was bark.

These equations were used to compute above-stump stand biomass based on measured diameters of loblolly pine on four small watersheds within the stand (Table 4). Above-stump biomass averaged about 110 t/ha. This figure appears low when compared to other biomass studies on loblolly pine plantations (Wells and others 1975, Nemeth 1972, Smith and others 1971, Switzer and Nelson 1972).

TABLE 3. Allometric regression equations for estimating above-stump biomass (kg) of components of 41-year-old loblolly pine trees from a managed plantation in the Piedmont of South Carolina.

Tree component	Regression equation	Coefficient of determination (r^2)	Standard error $S_{y \cdot x}$
Stem wood (5 cm top)	$\text{Log}_{10}Y = -1.2159 + 2.5249 \log_{10}\text{dbh}$	0.984	0.0496
Stem bark (5 cm top)	$\text{Log}_{10}Y = -1.5161 + 2.0383 \log_{10}\text{dbh}$	.956	.0670
Total stem (5 cm top)	$\text{Log}_{10}Y = -1.1053 + 2.4773 \log_{10}\text{dbh}$	.985	.0476
Total stem (15 cm top)	$\text{Log}_{10}Y = -1.1421 + 2.4818 \log_{10}\text{dbh}$	.951	.0460
Branches	$\text{Log}_{10}Y = -2.8857 + 3.1327 \log_{10}\text{dbh}$	.953	.1073
Foliage	$\text{Log}_{10}Y = -2.7273 + 2.5388 \log_{10}\text{dbh}$	.937	.1009
Complete tree	$\text{Log}_{10}Y = -1.1575 + 2.5641 \log_{10}\text{dbh}$	.985	.0482

TABLE 4. *Above-stump biomass (kg/ha) of loblolly pine on four watersheds within a 41-year-old managed plantation in the Piedmont of South Carolina.*

Watershed no.	Foliage	Branch	Total stem wood to a 5 cm top	Total stem bark to a 5 cm top	Total stem to a 5 cm top	Merch. stem[a] wood to a 15 cm top	Merch. stem bark to a 15 cm top	Total merch. stem	Total crown[b]	Total above-stump biomass
63	2,499	13,120	77,402	7,499	84,976	72,138	7,134	79,272	21,323	101,129
64	3,288	17,684	101,757	9,588	111,450	94,633	9,359	103,992	28,430	133,207
65	2,584	12,602	80,180	8,292	88,572	75,145	7,432	82,577	21,181	104,231
66	2,475	12,677	76,695	7,621	83,389	71,623	7,084	78,707	19,834	100,023
	2,712[c]	14,021	84,009	8,250	92,097	78,385	7,752	86,137	22,692	109,648
	(194)	(1,226)	(5,964)	(479)	(6,542)	(5,471)	(541)	(6,013)	(1,942)	(7,904)

[a] Merchantable stem wood and bark calculated from total merchantable stem biomass using a ratio of 91 percent wood and 9 percent bark.
[b] Total crown includes foliage, branches, and stem from 15 to 5 cm.
[c] $\bar{X}_{(s_{\bar{x}})}$.

TABLE 5. Average weighted nutrient concentrations for 41-year-old loblolly pine by tree component, based on 16 sample trees.

Tree component	N	P	K	Ca
		Percent		
Bole wood	0.064 ± 0.001[a]	0.005 ± 0.002	0.043 ± 0.002	0.077 ± 0.007
Bole bark	.176 ± .007	.011 ± .001	.049 ± .004	.166 ± .014
Branches	.188 ± .006	.018 ± .001	.085 ± .004	.223 ± .013
Foliage	1.065 ± .060	.106 ± .004	.233 ± .011	.209 ± .007

[a] $\bar{X} \pm s_{\bar{x}}$.

Differences are due to site quality and stand age. Stands in the cited studies were relatively young and growing on good to excellent sites, both of which contribute to their rapid annual accumulation of biomass. Our nearly mature stand had been thinned twice and was growing on a site of poor quality. Our figures also represent biomass predicted from trees measured on about 5 ha of this stand, rather than biomass expanded from small uniform plots. Thus, biomass values presented here are probably more representative of older managed plantations growing on eroded sites in the upper Piedmont.

We have compared our biomass equations with unpublished dbh equations developed by Taras and Clark (1974) for natural loblolly pine trees of similar size in Alabama. Above-stump biomass predicted from both sets of equations was similar and differed by less than 6 percent for a 35 cm tree to less than 2 percent for a 15 cm tree. However, there were some small but significant differences in predicted biomass of certain tree components, e.g., stem bark and foliage. Differences in season of sampling may have accounted for foliage differences. Another

TABLE 6. Allometric regression equations for estimating nutrient content of 41-year-old loblolly pine trees growing in a managed plantation in the upper Piedmont of South Carolina.

Tree component	Regression equation	Coefficient of determination (r^2)	Standard error $S_{y \cdot x}$
Stem wood N[a]	$\log_{10}Y = -4.5739 + 2.6399 \log_{10}\text{dbh}$	0.976	0.0606
Stem bark N	$\log_{10}Y = -4.2292 + 2.0040 \log_{10}\text{dbh}$	.921	.0850
Branches N	$\log_{10}Y = -5.3428 + 2.9363 \log_{10}\text{dbh}$	.961	.0912
Foliage N	$\log_{10}Y = -4.9963 + 2.7477 \log_{10}\text{dbh}$	.874	.1653
Stem wood P	$\log_{10}Y = -5.5945 + 2.5786 \log_{10}\text{dbh}$	.938	.0961
Stem bark P	$\log_{10}Y = -5.7282 + 2.2155 \log_{10}\text{dbh}$	.851	.1399
Branches P	$\log_{10}Y = -6.4119 + 2.9675 \log_{10}\text{dbh}$	.947	.1079
Foliage P	$\log_{10}Y = -5.8073 + 2.6154 \log_{10}\text{dbh}$	.921	.1214
Stem wood K	$\log_{10}Y = -4.4567 + 2.4294 \log_{10}\text{dbh}$	.931	.0962
Stem bark K	$\log_{10}Y = -4.7232 + 1.9516 \log_{10}\text{dbh}$	.778	.1513
Branches K	$\log_{10}Y = -5.5934 + 2.8641 \log_{10}\text{dbh}$	.949	.1017
Foliage K	$\log_{10}Y = -5.5829 + 2.6990 \log_{10}\text{dbh}$	.893	.1481
Stem wood Ca	$\log_{10}Y = -4.4146 + 2.5759 \log_{10}\text{dbh}$	.926	.1060
Stem bark Ca	$\log_{10}Y = -3.8359 + 1.6977 \log_{10}\text{dbh}$	.737	.1471
Branches Ca	$\log_{10}Y = -5.2016 + 2.8846 \log_{10}\text{dbh}$	.926	.1249
Foliage Ca	$\log_{10}Y = -5.4848 + 2.5948 \log_{10}\text{dbh}$	.911	.1287

[a] All stem values are to a 5 cm top. Y is in kg and dbh is in cm.

TABLE 7. Nutrient content (kg/ha) in above-stump biomass of a managed 41-year-old loblolly pine plantation in the upper Piedmont of South Carolina.

Component	N	P	K	Ca
Wood (to a 5 cm top)	54.3 ± 4.0[a]	4.2 ± 0.3	35.0 ± 2.4	63.1 ± 4.6
Bark (to a 5 cm top)	14.3 ± .8	.9 ± .1	3.9 ± .2	12.8 ± .6
Stem (to a 5 cm top)	68.5 ± 4.8	5.1 ± .4	38.9 ± 2.6	75.9 ± 5.1
Branches	25.1 ± 2.1	2.4 ± .2	11.1 ± .9	29.2 ± 2.4
Foliage	29.5 ± 2.3	3.0 ± .2	6.5 ± .5	5.7 ± .4
Crown[b]	60.5 ± 4.5	4.7 ± 1.5	21.1 ± 1.5	40.3 ± 2.9
Total above-stump[c]	123.2 ± 9.1	10.4 ± .8	56.4 ± 4.0	110.8 ± 7.9

[a] Means and standard errors, based on data from four watersheds ($n = 4$) within stand.
[b] Crown includes foliage, limbs, and stem (wood + bark) above a 15 cm top.
[c] Total includes wood, bark, branches, and foliage.

reason for our slightly lower percent foliage is that we separated the small portion of branchlet from the foliage, whereas Taras and Clark included it as foliage.

Above-stump biomass on three of the four watersheds ranged from 100 to 104 t/ha (Table 4). Watershed 64, which was less eroded, had 133 t/ha. Crown biomass was calculated as the sum of foliage, branches, and that part of the stem above 15 cm, i.e., the difference between total stem and merchantable stem biomass. Crown biomass represented about 20 percent of above-stump biomass and would be left on site in conventional logging systems but removed in whole-tree harvesting. The coefficient of variation was <7 percent for each of the biomass components when comparing each of the four watersheds (Table 4).

Management records from the Clemson Experimental Forest show that a total of 46.8 m^3/ha of wood and bark was removed from this stand in previous thinnings. Assuming these stems (wood + bark) had a specific gravity of 0.45, biomass of stems removed in earlier thinnings would equal 21,060 kg/ha. If stems accounted for 86 percent of the above-stump biomass on these thinned trees, foliage and branches left in the woods would have amounted to about 3,428 kg/ha. Thus, total above-stump pine biomass produced over the 41 years was about 134 t/ha. This total, of course, does not include annual litter fall (foliage, cones, bud scales, twigs, flowers, branches, and bark).

Nutrient Concentrations and Equations.—Concentrations of all nutrients generally were highest in the foliage, where they ranged from 1.07 percent for N to 0.11 percent for P (Table 5). Branches and bark contained concentrations intermediate between foliage and wood. There were few dead branches on trees in this stand because of previous thinnings, which allowed sunlight to penetrate the canopy and keep the lower branches alive. As indicated by the low standard errors, nutrient concentrations of each component varied little about the mean values.

The poor soil nutrient status is reflected in the low nutrient concentrations in the trees. Nutrient concentrations are generally lower, except for foliage N and P, than other reported nutrient concentrations for loblolly pine components (Metz and Wells 1965, Hinesley 1978). The low fertility and eroded condition of the soil account, in part, for the relatively poor productivity of the site. However, this condition is common on slopes of the upper Piedmont.

The fact that foliage, small branches, and the upper stem have high nutrient concentrations is important in regard to the effects of various harvesting and site preparation systems on nutrient conservation. Operational systems which utilize, remove, or concentrate slash will deplete site nutrients to a much greater degree than systems that leave slash in place (Bengtson 1981). As suggested by many

TABLE 8. Comparison of two methods of estimating nutrient content (kg/ha) of a 41-year-old loblolly pine plantation in the upper Piedmont of South Carolina.

	N		P		K		Ca	
Component	I[a]	II[b]	I	II	I	II	I	II
Stem wood	54.3	53.8	4.2	4.2	35.0	36.1	63.1	64.7
Stem bark	14.3	14.5	.9	.9	3.9	4.0	12.8	13.7
Branches	25.1	26.4	2.3	2.5	11.1	11.9	29.2	31.3
Foliage	29.5	28.9	3.0	2.9	6.5	6.3	5.7	5.7
Total above-stump	123.2	123.6	10.5	10.5	56.5	58.3	110.8	115.4

[a] Estimated from nutrient regression equations in Table 6.

[b] Estimated by multiplying average biomass of a component by its average weighted nutrient concentration.

researchers, depletion of nutrients at rates more rapid than they are replaced could contribute to declines in subsequent productivity on sites where nutrients are already marginally deficient.

Coefficients of determination (r^2) were relatively high for equations predicting nutrient content (Table 6) but not as high as those for biomass equations. The somewhat lower r^2 values for the nutrient equations reflect the fact that concentration was not closely related to biomass of a component. However, when concentration was multiplied by biomass and regressed against diameter, the relationship was strong because of the excellent relation between biomass and diameter.

Total nutrient contents of the various tree components of the plantation were calculated from the nutrient regression equations and measured diameters of all trees on the four watersheds (Table 7). Nitrogen was present in greatest quantities in the above-stump biomass, averaging 123.2 kg/ha, followed by Ca, K, and P. Although crown biomass accounted for only 20 percent of the above-stump biomass, it contained 49, 45, 37, and 36 percent of the N, P, K, and Ca, respectively. Harvesting systems that remove the nutrient-rich components of the stand, such as foliage, branches, and the upper stem, gain a relatively small amount of low-grade biomass at the expense of a relatively large quantity of nutrients removed from the site.

The question arises as to how the elemental contents of a stand as predicted by the nutrient regression equations compares with those determined by multiplying average biomass of components by average weighted concentrations. Few comparisons of this type have been made, and there is no standard method for computing nutrient content of stands. Both methods yielded similar estimates of stand nutrient contents, with the greatest difference for an element in any component being about 7 percent (Table 8). Since a regression line is essentially a moving average, it is perhaps not surprising that both methods give similar results.

It would be unwise to extend the nutrient equations for elemental contents to other areas. As Morrison and Foster (1979) have pointed out, forest chemistry data have value primarily in relation to specific sites. Nutrient concentrations in biomass may vary considerably from site to site. However, biomass equations are probably considerably less site specific than are nutrient content equations as evidenced by the close agreement between our equations and those of Taras and Clark. Therefore, nutrient contents of other near-maturity loblolly pine plantations of similar form and wood properties could be estimated by analyzing subsamples of biomass components from a relatively small number of trees (∝8–10) for nutrient content and multiplying those weighted concentrations by the dry weights predicted from the biomass equations presented here. Comerford and Leaf (1982a, 1982b) recently recommended a 20 percent systematic sample of foliage and branches to estimate crown nutrient content of individual red pine (*Pinus resinosa* Ait.) trees within 10 percent allowable error. They suggest that more than five discs will be necessary to estimate actual nutrient content of the stem within ±10 percent. Their recommendations need verification for loblolly pine.

Conclusions

Crowns of 41-year-old loblolly pine trees account for 20 percent of the above-stump biomass but contain nearly half of the N and P and over one-third of the K and Ca. Because of the distribution of nutrients in standing biomass, the use of harvesting and site preparation practices that remove or displace the nutrient-rich crown components should be carefully scrutinized. Above-stump biomass averaged about 110 t/ha on this eroded site, which reflects a much lower rate of annual net accumulation of biomass than reported in other loblolly pine biomass studies.

Nutrient content of a stand can be determined with about equal accuracy by using site-specific nutrient content regression equations or by multiplying average biomass of tree components by average weighted concentrations. To predict nutrient content of other loblolly pine stands of similar form and wood properties where nutrient concentrations are different, we suggest analyzing subsamples of biomass components for nutrient concentrations and applying those weighted concentrations to the biomass equations presented in this paper.

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Response of Populus *Hybrids to Aluminum Toxicity*

K. C. Steiner, J. R. Barbour, and L. H. McCormick

ABSTRACT. Twenty-two *Populus* clones, derived from various crosses among six species, were tested in solution culture for response to 3 ppm aluminum. Clonal mean responses varied from a maximum of 93 percent reduction in root elongation to a minimum of no reduction when compared with elongation in untreated solution. Hybrids derived at least in part from species in section *Tacamahaca* had significantly higher tolerances than those derived entirely from species in section *Aegeiros*. This difference is consistent with several reports of the performance of clones with similar pedigrees on moderately acid soils. The results confirm the relatively high Al-sensitivity of hybrid poplars, and they suggest a cause for some of the genotype × environment interactions that have occurred in trials of hybrid poplar. FOREST SCI. 30:404–410.

ADDITIONAL KEY WORDS. Tolerance, genotype-environment interaction.

ALUMINUM (AL) TOXICITY is often overlooked as a possible growth limiting factor for trees because the disorder most directly affects root growth and no unique symptom is produced in aboveground parts. Aluminum toxicity may be present in almost any inorganic soil with a pH less than 5.0–5.5, depending upon the sensitivity of the plant species (Foy 1974). Below these pH levels, the solubility and toxicity of Al increase rapidly (Black 1968). The best known and probably most extreme instances of Al toxicity to trees have occurred on coal mine spoils, which may have pH levels as low as 2.5. On such sites, tolerance to Al becomes a characteristic of overriding significance. Aluminum toxicity is unlikely to occur in trees indigenous and presumably adapted to undisturbed sites. However, such natural relationships may not exist in forest plantations, and of course natural relationships can be destroyed by disturbances such as acid precipitation.

Variation among tree species in tolerance to Al was demonstrated by McCormick and Steiner (1978). Among the species they tested, a poplar (*Populus*) hybrid clone (NE-388)

The authors are, respectively, Associate Professor of Forest Genetics, former graduate student, and Assistant Professor of Forest Resources, School of Forest Resources, The Pennsylvania State University, University Park, PA 16802. Journal Article No. 6010 of the Pennsylvania Agricultural Experiment Station. This research was supported by a grant from the U.S. Experimental Protection Agency through the Science and Education Administration/Cooperative Research, U.S. Department of Agriculture. The authors wish to acknowledge the assistance in obtaining plant material provided by the Pennsylvania Bureau of Forestry and the Northeastern Forest Experiment Station, and they thank M. E. Demeritt and J. W. Wright for their constructive comments on an earlier draft of the paper. Manuscript received 7 May 1981.