

# A TREE BIOMASS AND CARBON ESTIMATION SYSTEM

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**Abstract**—Appropriate forest management decisions for the developing woody biofuel and carbon credit markets require inventory and growth-and-yield systems reporting component tree dry weight biomass estimates. We have developed an integrated growth-and-yield and biomass/carbon calculator. The objective was to provide Mississippi's State inventory system with bioenergy economic development tools and forest landowners trying to qualify for carbon credit programs with carbon estimates. Biomass equations were collected from many sources in the literature and organized into a uniform software system that provides estimates of volume/biomass/carbon of branches, foliage, and bole. Users may select biomass components for 347 species/region combinations and obtain information on (1) tree profiles, (2) biomass/carbon tables, and (3) model forms and coefficients. Bole biomass and volume can be obtained to any top diameter limit. Pine (*Pinus* spp.) plantation and hardwood stand case studies demonstrate biomass and carbon estimation and pine projections. Alternative financial analyses generated by the growth-and-yield system provide information on which forest landowners may base management decisions for the biofuel and carbon markets if they provide current local stumpage prices.

## INTRODUCTION

Chicago Climate Exchange (CCX) members may mitigate carbon dioxide (CO<sub>2</sub>) emissions by purchasing carbon offsets generated by the reduction, avoidance, or sequestration of CO<sub>2</sub> (Grebner and others 2007, Rousseau 2008). Protocols for CO<sub>2</sub> emission offsetting using afforestation and managed forest activities have been defined and present a potential benefit to forest landowners trading in the carbon market. CCX protocols include reliable inventories, regional and species-specific carbon sequestration estimates, approved growth-and-yield models, and verification procedures. Elemental carbon (C) is fixed in various parts of a tree such as wood and bark during photosynthesis. The CO<sub>2</sub> equivalent produced by a tree is based on the premise that the oven-dried weight of the bole bark and wood is approximately one-half elemental C. In general, softwoods have more lignin and less hemicellulose than hardwoods and, consequently, softwoods have a higher C content per unit weight. C content also varies by tree species; however, one-half is the accepted conversion percentage for all tree species (Birdsey 1992). The weight ratio of CO<sub>2</sub> to elemental C is 3.67. Therefore, the CO<sub>2</sub> equivalent for the bole wood and bark of a tree is calculated as:

$$3.67 \frac{ODWt}{2} \quad (1)$$

where

ODWt = oven-dried weight of bole wood and bark

A carbon credit is defined as 1 t of CO<sub>2</sub> removed from the atmosphere and, in 2008, CCX C credit offsets traded between \$7.40 and \$0.95. Forestry offset projects trade-in units of at least 12 500 t/year, but small forest landowners can collectively trade through registered organizations called offset aggregators (Grebner and others 2007, Rousseau 2008).

Biomass and C estimates are needed to support the use of the newly developing C credit exchange and biofuel markets.

Decision-making tools are needed by forest landowners trying to qualify for C credit programs and bioenergy industries using Mississippi Institute for Forest Inventory data or other sources to assess the risk on investments in new facilities. Upgrades are necessary for volume calculators, inventory systems, and growth-and-yield models. The objectives of this paper are to: (1) present a comprehensive biomass and C estimation system that can be integrated with traditional volume estimation and prediction models and (2) demonstrate the use of this system by comparing total sequestered bole biomass and C for a cutover site-prepared loblolly pine (*Pinus taeda*) plantation and a natural red oak (*Quercus* section *Lobatae*)-sweetgum (*Liquidambar styraciflua*) bottomland hardwood stand. Although not presented in this paper, the accompanying software also includes updated growth-and-yield models for slash (*P. elliotii*) and longleaf pine (*P. palustris*).

## METHODS

The first step in developing the biomass/C estimation system was an exhaustive search of the literature for cubic volume and weight prediction equation systems for all major tree components for Gulf South and Southeastern United States tree species. Other regions of the United States and minor species were included when found. Many of the biomass systems in the literature were for bole wood only, but 41 were complete biomass systems that included at least bole, branches, and foliage. The core biomass/C estimation program was created as a Microsoft Windows® Dynamic Link Library (dll). A dll is a software program module that can be linked to other programs, e.g., Visual Basic, Excel, and FORTRAN. This dll estimates C, biomass by tree component, dry and green weights, and volume in all the conventional units.

The biomass/C dll was incorporated into an existing tree volume/weight table and equation generator called Tree Volume and Weight Calculator (TVoIWt). This computer

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program now contains a total of 347 prediction systems. The software interface provides the user with an option of reconciling one of the complete biomass systems with any bole-only profile function. The reconciliation process multiplicatively adjusts volumes and weights of branches and roots by the ratio of total bole volume from the profile system to total bole volume from the complete system. Justification of the procedure is based on the observation that the ratio of the volume of a biomass component to the total bole biomass volume is nearly a constant for all components. If a bole wood only profile equation is reconciled with a biomass system of a similar species, the ratios between total bole volume from the profile equation to total bole volume from the biomass system and biomass component volumes to total biomass bole volume should hold. If the user decides not to reconcile the profile and biomass prediction systems, separate volumes and weights are given. Biomass and C estimates for bark can be obtained by subtracting outside bark (o.b.) volumes/weights from inside bark volumes/weights.

Modifications were made to the TVolWt problem definition screen (fig. 1) to allow biomass equation selection and reconciliation with profile functions if the "Reconcile Biomass System With Profile Function" box is checked. One of three modes is selected from the "Operation" drop-down box to produce standard or local volumes and weight equations and tables or single-tree volumes and weights. Profile functions and biomass systems are chosen from lists. Sources and citations are documented in files that accompany the software. If the user selects "Local Volume Equations," sufficient diameter at breast height (d.b.h.)-merchantable height (HM) pairs (20 or more) must be entered in the interface spreadsheet to predict HM and form class (FC) equations to calculate local volumes (volumes that are a function of d.b.h. alone). Improved estimates of standard equations can also be obtained by providing d.b.h.-HM pairs. These data are used internally to develop guide curves for preparing equations. FC data is only required for those profile functions that involve the FC variable. Possible model forms, fitted to approximate standard and local volume or weight tables, HM, and FC equations, are printed at the end of each problem "Run." Volume tables are printed by checking the "Print Volume Tables" box and can be customized by specifying ranges and increments for d.b.h., HM, and FC. Volume and weight table entries are calculated directly from the profile function or biomass system and not from the fitted volume and weight equations. The tables are exact, and the equations, that only approximate the table entries, are given for the convenience of the user.

Growth-and-yield simulators for cutover site-prepared loblolly pine (Matney and Farrar 1992), cutover site-prepared slash pine (Zarnoch and others 1991), natural longleaf pine (Farrar and Matney 1994), and red oak-sweetgum bottomland hardwood stands (Iles 2008) were also modified to call the biomass/C dll. The red oak-sweetgum bottomland hardwood growth-and-yield model was obtained from a recently completed study in Mississippi funded by the U.S. Forest Service, Center for Bottomland Hardwoods Research. These

models allow landowners to explore different management scenarios in comparing the financial benefits of biofuel, C, and traditional markets.

## RESULTS

### Tree Volume and Weight Calculator (TVolWt)

The TVolWt problem definition screen in figure 1 depicts a standard volume equation operation for a reconciled white oak (*Q. alba*) Southwide profile function and Coastal Plain Gulf South biomass system. Custom inputs were specified for pulpwood and sawtimber d.b.h. thresholds, merchantable tops, volume table formatting, and "pounds per cubic foot (o.b.)." Tables were produced for 44 volume and weight units. Figures 2 and 3 represent volume and biomass system weight tables, respectively. Figure 4 is a representative section of the standard volume equation parameters and fit statistics for models 1 and 2, models that do not involve FC. Printed model forms for standard and local volumes, HM, and FC equations are given in figure 5. The oven-dried o.b. stem weights to a 0-inch stem top diameter in figure 3 are presented in pounds. To convert these figures from pounds to metric tons of CO<sub>2</sub> equivalents (C credits), the result of equation 1 is multiplied by 0.00045359. Oven-dried weights for small-diameter trees or branches and foliage can also be used to explore the opportunities for participating in the biofuel market that utilizes forest residuals and small diameter trees (Grebner and others 2009; Perez-Verdin and others, 2009). Stem profiles, volumes, and weights for individual trees can be obtained by selecting the "Single Tree Volume and Profile" operation on the problem definition screen. Figure 6 shows the individual tree results for a southwide loblolly pine plantation profile function reconciled with a Texas cutover loblolly pine biomass system.

### Growth-and-Yield Simulators

The modified cutover site-prepared loblolly pine and red oak-sweetgum bottomland hardwood stand growth-and-yield simulators were used to calculate accumulated elemental C and CO<sub>2</sub> equivalents of o.b. bole and branch components (table 1) (Schultz and others 2008). For purposes of comparison, high-, medium-, and low-quality site indices were chosen appropriate to each growth-and-yield model. Stands were evaluated for sequestered C at ages that represent the point of maximum mean annual increment and not financial maturity. Only bole C can currently be used in C credit calculations. Branch and foliage biomass are considered sources for biofuels. Loblolly pine stands reached maximum mean annual increment 19 to 16 years sooner than the red oak-sweetgum stands but accumulated almost one-half less C across high-, medium-, and low-quality site indices. These results are reflective of the higher carrying capacities attained by the hardwood stands. Yields from the cutover site-prepared loblolly pine growth-and-yield simulator are approximately 15 percent lower than those from old field growth-and-yield simulators. Since C credit programs register afforestation practices, the yields from the cutover site-prepared example should be increased by 15 percent for C market applications. An old field loblolly pine growth-and-yield simulator is available from the authors upon request.

**Select volume table/equation options**

Initial

Operation-> Standard Volume Equation  
 User Defined Standard Volume Equation  
 Local Volume Equations  
 Single Tree Volume and Profile

Built-in Profile Functions  
 802:9:SWide:WhiteOakAll:n=1060

Biomass system  
 802:1:CPInGulfSo:WhiteOak (14)

Reconcile biomass equation with profile function

OK  
 Cancel  
 Run Problem  
 1/20/2009  
 12:23:22 PM

	Dbh	Hm	FC
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
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41			
42			
43			

Merchantable Tops  
 At Hm-> 3  
 Pulpwood-> 3  
 Sawlog-> 8

Tree Variables  
 Dbh-> 15  
 Hm-> 75  
 FC-> 88

Volume Unit Selections  
 International-1/4 bf  
 Doyle bf  
 Scribner bf  
 Green pounds (o. b.)  
 Weight cord  
 Cunit (i. b.)  
 Cubic foot (i. b.)  
 Cubic foot (o. b.)  
 Print Volume Tables

Volume Table Formatting  
 Start End Inc.  
 Dbh-> 10 30 1  
 Start End Inc.  
 Hm-> 50 90 5  
 Start End Inc.  
 FC-> 84 92 2

Other Settings  
 Sawlog Length-> 16  
 Stump Height-> 0.5  
 Lbs/Cubic ft. (o. b.)-> 58.5  
 Lbs (o. b.)/Cord-> 5450

Form class calculation assumption [Outside or Inside bark at 17.3 feet ?]  
 FC = ( O.B. diameter at 17.3' )100/dbh  
 FC = ( I.B. diameter at 17.3' )100/dbh

Calculation assumptions  
 Pulpwood threshold dbh 4.6      Sawtimber threshold dbh 9.6  
 Percent bark for the Mesavage, and Behre variable bark percent model 119 to 122 0  
 Treat standard profiles as Mesavage/Behre merchantable/useable ht models  
 Check this box to prepare Mesavage/Behre equations on pulpwood dbh range  
 Cubic volume calculation rule/formula Smalian's  
 Cubic volume calculation bolt length 4  
 Use the Southern Doyle convention  
 Scribner rule approximation  $V = 0.79D^2 \cdot 2D - 4$  (Bruce, 1925)

Figure 1—Tree Volume and Weight Calculator (TVoWt) program interface used for collecting user preferences for generating standard and local volume and weight tables, equations, and single-tree component volume and weights.

Annual estimates of sequestered CO<sub>2</sub> equivalents in mt/acre are needed to estimate expected C market revenues. The four modified growth-and-yield simulators provided the basis for comparing revenues from different management strategies, e.g. thinnings, trees per acre, site index, and markets, e.g. C, biomass, pulpwood, sawtimber. Table 2 (Schultz and others 2008) summarizes calculations made from the results of the

cutover site-prepared loblolly pine simulator (Matney and Farrar 1992) for o.b. oven-dried weight of bole wood where site index is 60 (base age 25) and the number of trees per acre is 650 at age 5. Bole wood CO<sub>2</sub> equivalent per acre was estimated at 5-year intervals, and differences between intervals were divided by five to obtain the periodic annual bole CO<sub>2</sub> equivalent per acre. Expected average per-acre

Table 1. International-1/4 volumes (board feet) to a 8.0 inch sawlog top diameter (ob) limit for profile: 802:9:SWide:WhiteOakAll.

Dbh	Merchantable height									
	50	55	60	65	70	75	80	85	90	
10	40.7	44.7	48.9	53.5	58.7	63.2	68.9	74.9	81.0	
11	59.0	64.8	71.1	78.8	86.2	93.1	101.2	109.7	118.5	
12	77.4	86.8	94.6	104.3	114.1	123.3	133.8	144.8	156.3	
13	98.2	107.7	118.8	131.0	142.3	156.5	168.7	182.4	196.6	
14	120.0	131.8	145.3	159.2	173.7	189.9	205.7	221.2	241.0	
15	142.5	156.2	172.3	189.0	207.3	225.1	245.3	264.8	284.1	
16	166.6	184.8	201.4	222.1	241.9	264.3	285.0	310.7	333.2	
17	190.9	211.9	234.8	255.1	279.6	305.4	329.3	357.6	384.5	
18	216.4	240.2	266.0	291.4	318.7	348.0	376.1	408.5	437.9	
19	247.6	274.7	303.0	329.6	361.1	394.2	424.9	461.2	494.3	
20	275.0	306.0	337.6	369.6	404.0	440.9	475.1	515.4	558.9	
21	309.1	343.0	378.4	414.3	449.5	490.3	533.3	573.0	620.3	
22	344.1	381.9	414.6	457.5	500.7	541.2	588.7	638.6	684.1	
23	375.2	416.3	459.2	502.4	550.1	600.0	646.2	700.6	757.8	
24	413.8	459.2	506.5	554.3	606.6	655.4	711.6	771.5	826.0	
25	453.3	504.1	556.1	603.1	659.1	718.6	773.5	838.1	906.4	
26	487.6	541.9	597.6	658.6	720.4	777.9	844.5	915.1	979.6	
27	531.2	589.1	649.6	710.8	776.7	846.1	918.5	985.7	1065.8	
28	576.3	639.2	704.8	770.5	841.9	917.4	987.3	1068.9	1155.5	
29	622.5	690.4	761.9	832.6	902.1	982.3	1067.2	1155.4	1236.1	
30	671.0	744.2	807.1	889.4	972.4	1058.8	1150.1	1232.8	1332.0	

Figure 2—Representative volume (International 1/4-inch) table output from the Tree Volume and Weight Calculator (TVolWt) program for a white oak Southwide profile function that has been reconciled with a white oak Coastal Plain Gulf South biomass system.

Table 23. Stem DWOB (lbs) to a 0.0 inch stem top diameter(ob) limit for profile: 802:9:SWide:WhiteOakAll.

Dbh	Merchantable height									
	50	55	60	65	70	75	80	85	90	
10	590.45	651.56	705.99	769.13	825.63	889.41	955.11	1022.73	1092.33	
11	697.57	758.81	832.03	905.43	978.05	1052.72	1129.51	1208.42	1289.53	
12	801.69	882.71	953.98	1044.49	1127.24	1212.26	1299.56	1389.19	1481.14	
13	922.35	1001.31	1096.18	1190.90	1284.15	1390.68	1489.95	1591.80	1696.18	
14	1049.03	1138.15	1245.20	1352.05	1457.10	1577.20	1688.84	1803.23	1937.24	
15	1181.56	1280.98	1400.71	1519.98	1649.70	1771.06	1911.06	2039.88	2171.75	
16	1319.25	1449.15	1562.07	1706.78	1837.76	1987.60	2126.42	2287.98	2435.23	
17	1461.83	1604.92	1754.02	1888.08	2047.53	2213.93	2367.91	2547.12	2710.22	
18	1609.09	1765.43	1928.38	2090.31	2266.25	2449.72	2619.30	2816.80	2996.35	
19	1784.20	1957.62	2138.24	2300.30	2493.38	2694.62	2880.28	3096.61	3293.01	
20	1941.83	2129.30	2324.36	2518.00	2728.61	2948.11	3150.33	3386.17	3632.19	
21	2131.50	2337.29	2551.58	2764.12	2971.74	3209.93	3458.21	3684.93	3951.65	
22	2329.79	2554.63	2748.29	2998.29	3248.11	3479.83	3747.93	4027.44	4280.34	
23	2502.52	2742.33	2991.94	3239.40	3508.28	3788.36	4045.83	4346.40	4659.81	
24	2714.62	2974.68	3245.35	3513.69	3805.44	4075.85	4388.66	4714.71	5009.27	
25	2934.87	3216.05	3508.63	3769.80	4081.74	4406.49	4704.70	5052.91	5415.79	
26	3120.73	3417.76	3726.47	4063.20	4399.37	4710.56	5070.89	5446.21	5784.79	
27	3354.08	3673.36	4005.16	4333.76	4690.98	5062.88	5450.11	5802.40	6217.40	
28	3595.28	3937.78	4293.52	4645.74	5028.65	5427.27	5792.80	6219.88	6664.77	
29	3844.64	4210.90	4591.31	4968.10	5334.91	5756.10	6194.55	6651.21	7062.75	
30	4101.93	4492.50	4826.32	5260.05	5691.99	6141.35	6609.16	7034.23	7535.42	

Figure 3—Representative biomass component (stem oven-dried weight) table output from the Tree Volume and Weight Calculator (TVolWt) program for a white oak Southwide profile function that has been reconciled with a white oak Coastal Plain Gulf South biomass system.

Table 46. Standard volume/weight equations for profile: 802:9:SWide:WhiteOakAll.

Model	Unit	TopD	Parameter Estimates					Measures of Fit	
			a	b	c	d	e	Std.Error	FitIndex
1	cvobsm	0.0	2.265	0.0024665773				1.6061	0.9991
2	cvobsm	0.0	2.382	0.0028870821	1.96977	0.98257		0.4850	0.9999
1	cvibsm	0.0	2.103	0.0021684303				1.2158	0.9994
2	cvibsm	0.0	2.302	0.0023753107	1.97383	0.99586		0.4676	0.9999
1	gwobtsm	0.0	183.762	0.1561228391				196.5500	0.9966
2	gwobtsm	0.0	162.715	0.2431463321	1.90819	0.96123		30.2772	0.9999
1	gwibtsm	0.0	178.737	0.1381863348				180.5145	0.9964
2	gwibtsm	0.0	160.917	0.2148503692	1.89700	0.97075		29.4092	0.9999
1	dwobtsm	0.0	103.965	0.0912736342				123.9496	0.9961
2	dwobtsm	0.0	94.677	0.1385117586	1.88163	0.98916		17.8525	0.9999
1	dwibtsm	0.0	105.810	0.0797097231				123.0889	0.9948
2	dwibtsm	0.0	94.171	0.1299942146	1.85977	0.98892		16.9925	0.9999
1	cvobbran	-1.0	-0.519	0.0013729256				7.0903	0.9632
2	cvobbran	-1.0	0.321	0.0003032810	2.63155	0.86408		0.3273	0.9999
1	cvibbran	-1.0	-0.484	0.0010644915				5.9172	0.9584
2	cvibbran	-1.0	0.223	0.0002037444	2.67461	0.86478		0.2600	0.9999
1	gwobbran	-1.0	-38.018	0.0913986562				458.2929	0.9650
2	gwobbran	-1.0	11.862	0.0223332821	2.61377	0.85378		22.3967	0.9999
1	gwibbran	-1.0	-36.466	0.0716282796				387.4986	0.9602
2	gwibbran	-1.0	5.314	0.0152342704	2.65118	0.85829		18.1955	0.9999
1	dwobbran	-1.0	-26.081	0.0561738072				279.0114	0.9656
2	dwobbran	-1.0	6.866	0.0127870624	2.59283	0.88866		13.6434	0.9999
1	dwibbran	-1.0	-22.660	0.0439591260				228.2248	0.9630
2	dwibbran	-1.0	3.248	0.0094570068	2.61497	0.88504		11.0245	0.9999
1	gwfoli	-1.0	16.133	0.0092243541				20.2885	0.9903
2	gwfoli	-1.0	8.110	0.0284082380	2.19803	0.55751		1.3708	1.0000
1	dwfoli	-1.0	6.735	0.0049252883				8.2217	0.9946
2	dwfoli	-1.0	4.464	0.0096604025	2.20113	0.66668		0.8108	0.9999

Figure 4—A representative section of the standard volume/weight equation parameters and fit statistics table produced by the Tree Volume and Weight Calculator (TVoIWt) program for a white oak Southwide profile function that has been reconciled with a white oak Coastal Plain Gulf South biomass system.

revenues from selling C offsets can be obtained by multiplying the periodic annual CO<sub>2</sub> equivalent per acre (table 2) by the CCX price per mt and summing over the contract period. Note in the loblolly pine example that maximum periodic CO<sub>2</sub> sequestered per acre occurs between years 20 and 25.

## DISCUSSION AND SUMMARY

A comprehensive computational model was created as a dll to estimate biomass and C for the major commercial species in the Eastern and Southern United States. Limited minor species and species from other areas are also included. The utility of the dll is extensive since it can be incorporated into other programs that allow dll linkages. The number of biomass/C systems incorporated into the dll was limited by the number of published systems, but projections made from

reconciling a profile function with a biomass system of a species with similar form and wood density should produce good estimates for species whose biomass estimates are not available.

A tree volume/weight table and equation generator (TVoIWt) and four growth-and-yield systems were modified to call the dll and can be used to simulate scenarios and evaluate the costs and benefits of participation in the biofuel markets or C offset program. For a complete C offset financial analysis, fees and costs associated with sales, registration, aggregators, verifiers, and inventories (Rousseau 2008) must also be estimated. Example applications showed that bottomland red oak-sweetgum hardwood stands produced higher bole and branch biomass than cutover site-prepared loblolly pine and

Standard Volume Equation Model Forms		Local Volume Equation Model Forms	
Model	Model Form	Model	Model Form
1	$v = a + b(\text{dbh}^2)(\text{Hm})$	1	$v = a + b(\text{dbh}^2)$
2	$v = a + b(\text{dbh})^c(\text{Hm})^d$	2	$v = a + b(\text{dbh})^{2d}$
3	$v = a + b(\text{dbh}^2)(\text{Hm})(\text{FC})$	3	$v = a + b(\text{dbh})^2 + c(\text{dbh})^4$
4	$v = a + b(\text{dbh})^c(\text{Hm})^d(\text{FC})^e$	4	$v = a + b(\text{dbh})^{2d} + c(\text{dbh})^{4d}$

  

Merchantable Height Equation Models		Form Class Equation Model Forms	
Model	Model Form	Model	Model Form
1	$\text{Hm} = a e^{\frac{b}{\text{dbh}}}$	1	$\text{FC} = a + b \text{dbh}$
2	$\text{Hm} = a e^{\frac{b}{\text{dbh}^c}}$	2	$\text{FC} = a + b(\text{dbh})^c$
3	$\text{Hm} = a + b \text{dbh}$		
4	$\text{Hm} = a + b(\text{dbh})^c$		

Figure 5—Model forms used in the Tree Volume and Weight Calculator (TVolWt) program for standard and local volumes, merchantable heights, and form class equations.

**Table 1—Total bole and branch outside bark elemental carbon sequestered per acre and CO<sub>2</sub> equivalent for low-, medium-, and high-quality site index cutover site-prepared loblolly pine plantations and natural red oak-sweetgum bottomland hardwood stands [elemental carbon was estimated at ages representing the point where mean annual increment is maximized (Schultz and others 2008)]**

Condition	Site index <sup>a</sup>	Age at maximum MAI years	Elemental carbon	
			Bole (o.b.) ----- mt/acre -----	Branch (o.b.)
Cutover site-prepared loblolly pine plantation	Low (45)	30	17.65 (64.78) <sup>b</sup>	2.74 (10.06) <sup>b</sup>
	Medium (60)	27	26.57 (97.51)	1.43 (5.25)
	High (75)	25	35.17 (129.07)	1.10 (4.04)
RO-SG bottomland hardwood stand	Low (80)	49	34.68 (127.28)	7.95 (29.18)
	Medium (100)	45	48.10 (176.53)	14.41 (52.88)
	High (120)	41	59.60 (218.73)	21.42 (78.61)

MAI = mean annual increment; o.b. = outside bark; RO-SG = natural red oak-sweetgum.

<sup>a</sup> Site index is base age 25 for the pine plantations and base age 50 for the hardwood natural stands.

<sup>b</sup> CO<sub>2</sub> equivalent weight equals elemental carbon weight times 3.67.

Table 1. Stem diameters and volumes of a 15.0 dbh tree with a merchantable height of 75 to a 3.0 top diameter for profile: 131:9:SWide:LobPinePln.

Profile			Volume units and top diameter(ob)		
h	Dia(ob)	Dia(ib)	Unit	Volume	TopDia
0.5	16.1	15.3	International-1/4	225.1	8.0
2.5	15.4	14.6	Doyle	132.0	8.0
4.5	15.0	14.2	Scribner	190.9	8.0
8.5	14.4	13.6	Cubic feet(o.b.)	40.94	8.0
12.5	13.8	13.0	Cubic feet(i.b.)	36.39	8.0
16.5	13.3	12.5	Green pounds(o.b.)	2395.0	8.0
17.3	13.2	12.4	Weight cords	0.439	8.0
20.5	12.7	12.0	Cunits(i.b.)	0.364	8.0
24.5	12.2	11.5	Cubic feet(o.b.)	45.24	3.0
28.5	11.7	11.0	Cubic feet(i.b.)	40.20	3.0
32.5	11.1	10.4	Green pounds(o.b.)	2646.4	3.0
36.5	10.5	9.9	Weight cords	0.486	3.0
40.5	9.9	9.3	Cunits(i.b.)	0.402	3.0
44.5	9.2	8.6	Cubic feet(o.b.)	45.45	0.0
48.5	8.5	8.0	Cubic feet(i.b.)	40.39	0.0
52.5	7.8	7.3	Green pounds(o.b.)	2658.8	0.0
56.5	7.0	6.6	Weight cords	0.488	0.0
60.5	6.2	5.9	Cunits(i.b.)	0.404	0.0
64.5	5.4	5.1			
68.5	4.5	4.3			
72.5	3.6	3.4			
75.0	3.0	2.9			
Total stem outside bark cubic volume.:				45.45	
Total stem inside bark cubic volume.:				40.39	
Total stem outside bark green weight.:				2808.29	
Total stem inside bark green weight.:				2624.83	
Total stem outside bark dry weight.:				1306.24	
Total stem inside bark dry weight.:				1206.28	
Branch outside bark cubic volume.:				6.30	
Branch inside bark cubic volume.:				5.68	
Branch outside bark green weight.:				350.91	
Branch inside bark green weight.:				340.38	
Branch outside bark dry weight.:				147.85	
Branch inside bark dry weight.:				142.07	
Green weight of foliage.:				1.33	
Dry weight of foliage.:				0.66	
Outside bark cubic volume to PW top.:				45.24	
Inside bark cubic volume to PW top.:				40.20	
Outside bark green weight to PW top.:				2785.41	
Inside bark green weight to PW top.:				2609.50	
Outside bark dry weight to PW top.:				1296.91	
Inside bark dry weight to PW top.:				1200.57	
Outside bark cubic volume to ST top.:				40.94	
Inside bark cubic volume to ST top.:				36.39	
Outside bark green weight to ST top.:				2463.61	
Inside bark green weight to ST top.:				2346.21	
Outside bark dry weight to ST top.:				1155.60	
Inside bark dry weight to ST top.:				1088.43	

Figure 6—Tree Volume and Weight Calculator (TVolWt) example stem profile, volume, and weight outputs for an individual tree using a Southwide loblolly pine plantation profile function reconciled with a Texas cutover loblolly pine biomass system.

**Table 2—Total outside bark bole cubic-foot volume, elemental carbon sequestered, carbon dioxide equivalent per acre, and periodic annual sequestered carbon dioxide equivalent per acre for a site index 60 (base age 25) loblolly pine plantation with 650 trees per acre at age 5 (Schultz and others 2008)**

Year	Bole o.b. <i>cubic-foot volume per acre</i>	Bole elemental carbon ----- <i>mt/acre</i>	Bole CO <sub>2</sub> equivalent <sup>a</sup> ----- <i>mt/acre</i>	Periodic annual increment (5-year periods) of bole sequestered CO <sub>2</sub> equivalent -----
10	518	5.14	18.86	
15	1299	9.84	36.11	3.45
20	2104	14.95	54.87	3.75
25	2844	19.99	73.36	3.70
30	3515	24.36	89.40	3.21
35	3999	27.72	101.73	2.47
40	4309	30.08	110.39	1.73

o.b. = outside bark; CO<sub>2</sub> = carbon dioxide.

<sup>a</sup> CO<sub>2</sub> equivalent weight equals elemental carbon weight times 3.67.

arrived at a maximum mean annual increment at an older age, indicative of the hardwoods' larger crowns and greater carrying capacity. Over 5-year intervals from age 10 to 40, the periodic annual increment for loblolly pine occurred between ages 20 and 25 depending on site index and planting density. Sequestered CO<sub>2</sub> per acre per year fell off sharply after age 30. Forest landowners can use the growth-and-yield simulators to determine maximum CO<sub>2</sub> sequestration by varying trees per acre, site index, and thinning regimes within the bounds of their overall management objectives and CCX requirements.

TVolWt, the four growth-and-yield systems, and the core dll program are available for downloading from [www.timbercruise.com](http://www.timbercruise.com). Future development of the dll will allow its use in standard timber cruise software for estimating tree component volume and weights.

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