A Carbon Estimation System: Rural and Urban Forest Case Studies

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Abstract
Web-based software developed by the Forest and Wildlife Research Center (FWRC) at Mississippi State University (MSU) in cooperation with the Mississippi Institute for Forest Inventory (MIFI) provides southeastern United States forest landowners with the biometrical tools necessary to help them evaluate their forest inventories for sequestered carbon. The software not only estimates carbon but also provides biomass, volume, and dry and green weight estimates of individual trees to any top diameter limit. Users may select biomass components for 347 species/region combinations and obtain information on 1) tree profiles, 2) biomass/carbon/volume tables, and 3) equations to approximate the tables. A growth and yield interface for loblolly (*Pinus taeda* L.), longleaf (*Pinus palustris* Mill.), and slash (*Pinus elliottii* Engelm.) pines allow users to specify age, site index, trees/acre, and basal area/acre. Actual case studies demonstrated biomass/carbon estimation and projections for pine and hardwood forest stands and a medium-sized municipal urban forest.

Keywords: Biomass, carbon sequestration, growth and yield, software

Introduction
Concern over potential environmental effects of carbon emissions in the United States (U.S.) has spawned national, state, and local programs to offset or store carbon in forests and forest products. Forest based carbon credits were sold on the Chicago Climate Exchange (CCX) between May and September of 2008 from $7.40 to $1.55/tonne CO_2, (www.chicagoclimatex.com/market/data/monthly.jsf) presenting a potential benefit for forest landowners. Small, nonindustrial private forest (NIPF) landowners trading less than 12,500 tonne/yr can collectively trade carbon through registered agents called offset aggregators (Grebner et al., 2007; Rousseau, 2008). However, they must meet specific protocols that include reliable inventories, regional and species specific carbon sequestration estimates, approved growth and yield models, and verification procedures. A carbon credit is defined as one metric tonne of CO_2 removed from the atmosphere. In determining how much CO_2 carbon is sequestered by a tree, 50% of the oven dry weight of bole wood and bark is considered elemental carbon (Birdsey, 1992). The CO_2 equivalent of elemental carbon is determined by multiplying the weight of elemental carbon by 3.67, the ratio of the weight of CO_2 to C. Current CCX protocols for calculating a carbon credit specify measuring outside bark (ob) bole wood only.

The carbon credit exchange market and the use of forest products for biofuels necessitates the upgrading of growth and yield models, and large- and small-scale inventory systems to output component biomass and carbon estimates in addition to the traditional merchantable volume and green weight estimates. This upgrade requires the development of an individual tree component volume, biomass, and carbon estimation computer program that can be incorporated into existing growth and yield models or inventory programs to extend their applicability. The purpose of this paper is to present a carbon/biomass estimation system and compare total sequestered bole carbon for a: 1) medium-sized municipal setting, 2) cutover site prepared loblolly pine (*Pinus taeda*, L.) plantation, and 3) a natural red oak (*Quercus* section *Lobatae*) - sweetgum (*Liquidambar styraciflua* L.) bottomland hardwood stand in the Gulf South region of the United States.

Methods

For the municipal setting, we created a Microsoft Windows Dynamic Link Library (dll - a software program module that can be linked to other programs) application and a tree biomass component estimation user interface that derives its computational basis from the dll. Microsoft Excel was used to illustrate the application of the dll by adding a Microsoft Excel user defined function to calculate carbon on a single tree basis. For pine plantation and hardwood forest stand settings, growth and yield models were modified to estimate biomass and carbon.

The first step in developing the carbon/biomass estimation system was the undertaking of an exhaustive search of the literature for cubic volume and weight prediction equation systems. Our goal was to construct a program that would estimate volumes and weights for all major tree components for Gulf South and southeastern U.S. tree species. Species from other areas of the country were included in the system when found. Most studies, however, only provide equations to estimate bole volumes and weights because of the high cost associated with separating components into bark, branches, and foliage, or the need to estimate the non-bole biomass components was not considered necessary at the time. Since an existing version of a program that calculates tree volume and weights, Tree Volume and Weight calculator (TVolWt) (www.timbercruise.com), already had 375 bole-only volume and weight tree profile based estimation systems, we decided to add the 41 complete biomass systems we pieced together from the literature to that program. We made assumptions to predict the other tree components and allow the user to associate and reconcile a complete system with any of the bole-only systems. The reconciliation procedure that we adopted was to multiplicatively adjust volumes and weights of branches and roots of the complete system by the ratio of (Total bole volume (ob) from the profile system)/(Total bole volume (ob) from the complete system) for ob components and the ratio of (Total bole volume (ib) from the profile system)/(Total bole volume (ib) from the complete system) for inside bark (ib) components. Our justification for the system reconciliation was predicated on the observation that the regression of the ratio of a biomass component to total bole volume is nearly a constant (the slope coefficient is 0). Thus, if a complete system were associated with an incomplete system of a similar species, the component ratio should hold. The burden of judging the appropriateness of an association and reconciliation is placed on the user of TVolWt. The user has the option to not reconcile systems and obtain independent estimates from each system.

Data and Models

Tree data for the estimate of carbon sequestered by street trees in Hattiesburg, Mississippi, were obtained by taking a 20% sample of the total length of all street segments in Hattiesburg and measuring all trees found within 30 feet of the curb on every segment selected (Grado and Jones, 2005). Segments were randomly selected from the Hattiesburg street map until 20% of the total street segment lengths were included in the sample. The total length of all streets was 155,150 feet and the sampled length 31,030 feet. With the 30 foot offset from the street, the total sample area was 106.85 acres, and the area sampled was 21.37 acres. Species, diameter at breast height (dbh), total height, and crown width in two perpendicular directions were recorded for every tree within the offset distance from the curb. These observations were inserted into a Microsoft Excel workbook and an Excel user defined function was written using the biomass system dll to calculate an estimate of the elemental carbon (1/2 of the total dry weight ob of the bole) stored in each sampled tree's bole. The user defined function takes the inputs of species code, dbh, and total height, assigns a profile and biomass system to the species, and returns the elemental carbon stored. The CO_2 equivalent is 3.67 times the return value of the user defined function.

Growth and yield models for cutover site-prepared loblolly pine, cutover site-prepared slash pine (*Pinus elliottii* Engelm.), and natural longleaf pine (*Pinus palustris* Mill.) were based on work by Matney (1992), Zarnoch et al. (1991), and Farrar and Matney (1994), respectively. The red oak-sweetgum bottomland hardwood growth and yield model was based on a recently completed study (Iles, 2008) in Mississippi funded by the USDA Forest Service Center for Bottomland Hardwoods Research.

Results

The installer for the dll and interface program are available at the www.timbercruise.com download center as Tree Volume and Weight calculator (TVolWt). This installs the interface, dll, example Excel workbook, Microsoft Visual C++ and Visual Basic projects calling the dll, and a PDF instruction manual on using the interface program and dll. Growth and yield programs implementing the dll for thinned cutover site-prepared plantation loblolly pine, cutover site-prepared plantation slash pine, and repeatedly thinned natural longleaf pine are also available at www.timbercruise.com. These growth and yield models now produce stand and stock tables showing ib and ob cubic foot volumes and green and dry weights of all tree components (i.e., bole, branches, foliage, roots). The dll has also been incorporated into the Mississippi Institute of Forest Inventory (MIFI) Dynamic Inventory Report software suite available at www.mifi.ms.gov or www.timbercruise.com. Future development will allow the dll to be used with a standard timber cruise for estimating tree component volume and weights.

Figure 1 shows the TVolWt problem setup screen. The user can select from the "Operation" drop down list to produce standard or local component volume and weight equations or tables, or to calculate volumes and weights for a single tree for the selected profile-biomass system association. The systems will be reconciled if the "Reconcile biomass system with profile function" box is checked. A partial output for the standard volume equation estimation functions for the selected system in Figure 1 is given in Figure 2. Figure 3 shows the weight table for total bole dry weight ib produced when the check box "Print Volume Tables" is checked. Table formatting is controlled by settings in the "Volume Table Formatting" section.

Form class (FC) is required only for profile functions with the suffix "–FC". By default FC = 100[Diameter (ob) at the top of the first 16 foot log/dbh]. Normally FC is defined as 100[Diameter (ib) at the top of the first 16 foot log/dbh]. To force the interface program to use the traditional FC definition, the second radio button must be selected in the "Form class calculation assumption" box. Dialog fields not applicable to an operation are always shaded in gray.

The local equation generation option requires sufficient (20+) dbh, merchantable height, and FC data pairs to calculate merchantable height and FC prediction equations required to calculate local volumes (volumes that are a function of dbh alone). FC data pairs are only required for profile functions involving the variable FC. Improved standard equations are fitted when these curves are constructed because the grid points generated for the least squares fitting of volumes to the functions are centered on the height and FC curves.

"Model" and "Unit" columns in Figure 2 reference the equation form fitted for the volume/weight component abbreviation in the "Unit" column. Results from all models appropriate to the "Operation" chosen in the problem setup screen (Figure 1) are reported. The possible model forms fitted to approximate standard and local volume or weight tables are given in Table 1. The user should note that the volume/weight table entries are calculated directly from the profile-biomass system and not from the fitted volume and weight equations. The tables are exact; whereas, the functions only approximate the table entries. A complete description of the settings on the problem setup screen is given in a PDF formatted file installed with the TVolWt software.

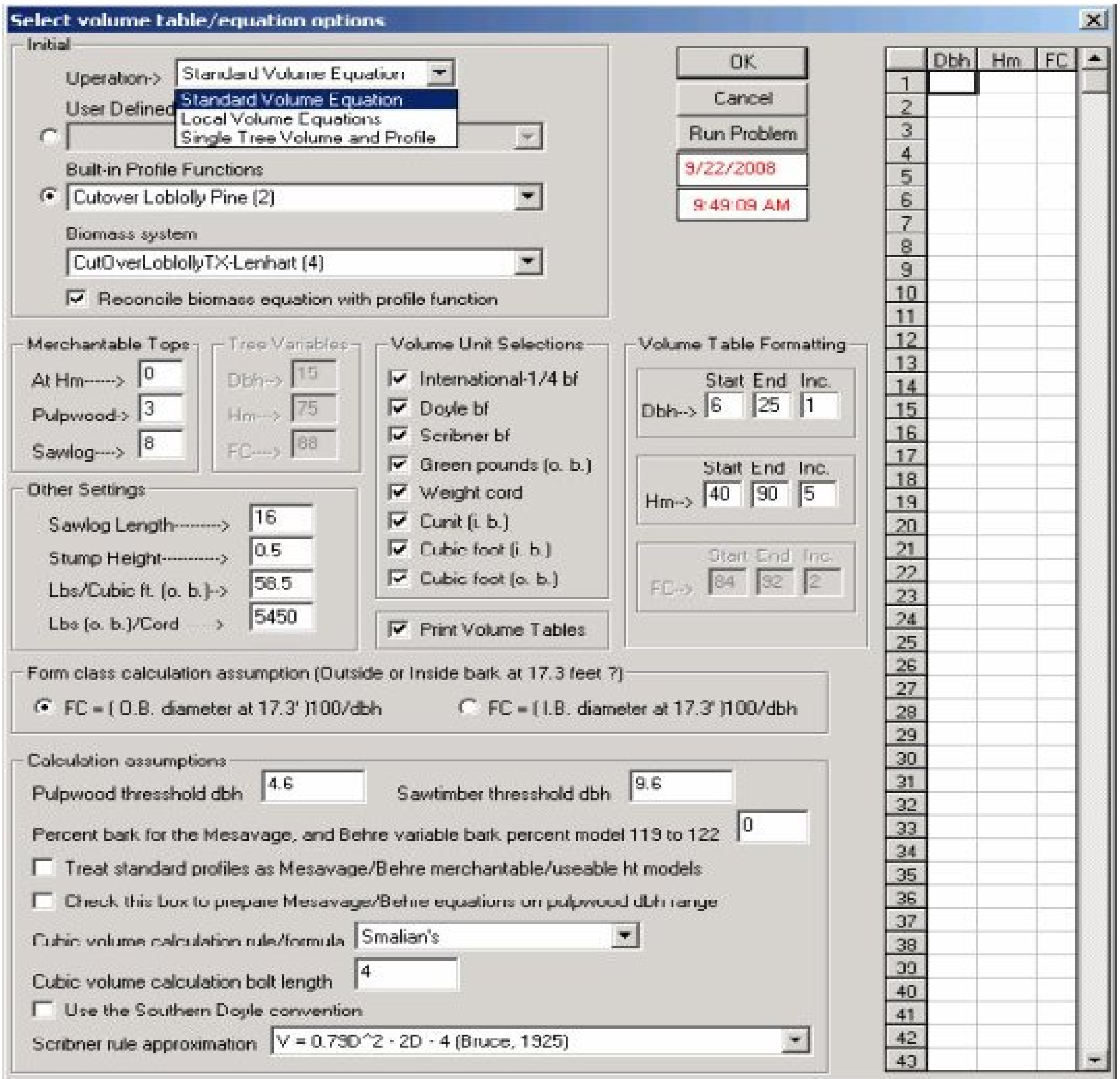

Figure 1. Tree Volume and Weight calculator (TVolWt) problem definition setup screen used to collect user preferences for generating standard and local volume/weight tables and equations and single tree component volume and weights.

Table 2. Standard volume equations for profile: Cutover Loblolly Pine (2).

			Parameter Estimates					Measures of Fit	
Model	Unit	TopD	a	b	c	d	e	Std.Error	FitIndex
1	cvobsm	0.0	0.503	0.0025965048				1.3958	0.9996
2	cvobsm	0.0	0.210	0.0036675736	2.00506	0.91521		0.2603	1.0000
1	cvibsm	0.0	0.400	0.0021213177				1.1282	0.9996
2	cvibsm	0.0	0.156	0.0029914504	2.00465	0.91593		0.1966	1.0000
1	gwobtsm	0.0	67.794	0.1451485228				150.9174	0.9983
2	gwobtsm	0.0	14.717	0.1049049989	1.91582	1.14279		15.6036	1.0000
1	gwibtsm	0.0	71.547	0.1304411627				57.8746	0.9997
2	gwibtsm	0.0	10.834	0.1690603115	1.94289	0.98491		12.4047	1.0000
1	dwobtsm	0.0	51.843	0.0655255325				82.0575	0.9976
2	dwobtsm	0.0	5.752	0.0536687917	1.87314	1.14765		7.1122	1.0000

Figure 2. A partial listing of the volume and weight equations generated by the Tree Volume and Weight calculator (TVolWt) program problem definition depicted in Figure 1 for a cutover loblolly pine plantation.

Table 12. Stem DWIB volumes and weights to a 0.0 inch Stem top diameter(ob) limit for profile: Cutover Loblolly Pine (2).

	Merchantable height										
Dbh	40	45	50	55	60	65	70	75	80	85	90
6	100.48	111.92	123.51	135.22	147.05	159.04	171.14	183.40	195.77	208.29	220.96
7	134.75	150.13	165.70	181.38	197.28	213.35	229.58	246.01	262.63	279.41	296.40
8	173.87	193.63	213.66	233.95	254.44	275.14	296.09	317.30	338.71	360.37	382.28
9	217.53	242.39	267.45	292.79	318.44	344.39	370.62	397.12	423.93	451.05	478.49
.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
24	1409.73	1570.55	1733.21	1897.73	2064.11	2232.27	2402.23	2574.13	2747.99	2923.74	3101.45
25	1523.77	1697.60	1873.32	2051.09	2230.88	2412.77	2596.55	2782.35	2970.25	3160.28	3352.34

Figure 3. The total bole dry weight inside bark (ib) weight (lbs) per acre table produced by the Tree Volume and Weight calculator (TVolWt) for the problem definition depicted in Figure 1 when the check box "Print Volume Tables" is selected. For brevity, not all rows in the table above are shown.

Table 1. Standard and local volume and weight (v) equation model forms used to approximate tree volume tables, where D, H, and F are tree dbh, height and form class, and model parameters are a, b, c, d, and e.

Model No.	Standard volume or weight model form	Local volume or weight model form
1	$v = a + bD^2H$	$v = a + bD^2$
2	$v = a + bD^cH^d$	$v = a + bD^{2c}$
3	$v = a + bD^2HF$	$v = a + bD^2 + cD^4$
4	$v = a + bD^cH^dF^e$	$v = a + bD^{2d} + cD^{4e}$

TVolWt and the growth and yield simulators were used to calculate total accumulated elemental carbon and CO_2 equivalent per acre for street trees in Hattiesburg, MS, a loblolly pine plantation, and a natural red oak-sweetgum bottomland hardwood mixture (Table 2). Calculations accumulated carbon for forest grown trees to the age that represented the maximization of mean annual increment (MAI) and not financial maturity. Medium and high site index (SI) red oak-sweetgum bottomland hardwood stands sequestered higher total carbon than low, medium, and high SI loblolly pine plantations and urban street trees. This is because the natural red oak-sweetgum bottomland hardwood stands typically have a higher bole wood carrying capacity than loblolly pine stands.

Total bole carbon per acre for open grown Hattiesburg street trees was slightly higher than for the low site index loblolly pine plantation. Street tree soils are often disturbed and compacted, and drainage patterns have been altered or blocked. Rooting area may be restricted by pavement and poor soil and drainage conditions. Also, street tree species may be selected for their lack of apical dominance and moderate heights or other factors, which result in more branch biomass and less bole biomass.

Total branch carbon was highest for the medium and high site index red oak-sweetgum bottomland followed by urban street trees. Open grown street trees retain limbs longer than densely planted, naturally pruning pine plantations, and natural bottomland hardwoods possess larger crowns with longer, heavier branches. Because of the unavailability of estimation equations for urban trees, we used equations based on forest trees to estimate open grown urban tree branch biomass, and they are unlikely underestimated.

Table 2. Total bole and branch outside bark (ob) elemental carbon sequestered per acre and CO_2 equivalent for low, medium, and high site index loblolly pine plantations and natural red oak-sweetgum (RO-SG) bottomland hardwood stands and the street trees (within 30 ft from curb) for a medium sized municipality (Hattiesburg, MS). Elemental carbon was estimated at ages representing the point where mean annual increment (MAI) is maximized.

Condition	**Site index**[1]	**Age at maximum MAI**	**Bole (ob) elemental carbon**	**Branch (ob) elemental carbon**
			··············· tonne/acre	················
Loblolly pine plantation	Low (45)	30	17.65 (64.78)[2]	2.74 (10.06)[2]
	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)
Hattiesburg, MS street trees	Unknown	Variable	22.88 (83.97)	12.70 (46.61)

[1] Site index is base age 25 for the pine plantations and base age 50 for the hardwood natural stands.
[2] CO_2 equivalent weight equals elemental carbon weight times 3.67.

Annual average carbon sequestration estimates were calculated from the loblolly pine growth and yield simulator output (Table 3). Landowners who are considering enrolling in a carbon offset program can use the growth and yield simulator to build scenarios that match their specific circumstances and assist them in comparing the costs and benefits of participation. An estimate of expected revenues [not including sales, registration, aggregator, and verifier fees or costs for inventories or management (Rousseau, 2008)] from selling carbon offsets can be obtained by multiplying the average bole CO_2 sequestered per acre per year in the last column of Table 3 by the CCX price per tonne of CO_2 and summing the product over the term of the contract period (15 years for managed forests). More complete tree biomass estimates that include bole, branches, and foliage can also be obtained from the growth and yield simulators for evaluating the potential of other uses such as biofuels (Grebner et al., In press; Perez-Verdin et al., In press).

Table 3. Total outside bark (ob) bole cubic foot volume, elemental carbon sequestered, carbon dioxide (CO_2) equivalent per acre, and carbon dioxide equivalent per acre per year for a site index 60 (base age 25) loblolly pine plantation with 650 trees per acre at age 5.

Year	Bole ob (ft^3 volume/acre)	Bole elemental carbon (tonne/acre)	Bole CO_2 equivalent[1] (tonne/acre)	Average bole CO_2 sequestered/acre/yr for 5-yr periods (tonne/acre)
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

[1] CO_2 equivalent weight equals elemental carbon weight times 3.67.

Discussion and Summary

Municipalities need information on costs and benefits associated with urban forests (Grado et al., 2008) to assess their environmental, social, and economic impacts. Together with an estimate of total CO_2 emissions, a municipality can use the carbon sequestration information provided by TVolWt to: 1) plan emission offsets in becoming a more carbon neutral community, 2) encourage community and industry participation in urban forestry, 3) strengthen the justification for urban forestry programs, and 4) explore using benefit/cost ratios to include carbon credits. CCX protocols are currently in place for urban tree planting and at least one organization is listed as an approved CCX offset project verifier for urban forestry (www.chicagoclimatex.com/content.jsf?id=102).

NIPF landowners who are considering enrolling in a carbon offset program can use the growth and yield simulators to build scenarios that imitate their specific circumstances and assist them in comparing the costs and benefits of participation. We recognize that the carbon estimation system does not have sufficient equations to cover all species, regions, and growing conditions (e.g., plantation, natural, open grown), but it is a starting point upon which to build. Carbon credits are accumulated on the basis of bole carbon CO_2; and, for a tree of a given species, choosing a profile and biomass system of a species of similar form and wood density should produce a good estimate.

While the TVolWt program is useful in its own right, the utility of the basis dll is more extensive as it can be incorporated into MS Excel via the Visual Basic editor, and into programs written in Visual C++, Visual Basic, or any other computer language that allows dll linkages. Example projects that integrate the dll are distributed with the TVolWt installer (www.timbercruise.com).

Biomass systems incorporated in the dll allow the user to obtain estimates for major commercial species in the eastern and southern U.S., but species for the remainder of the country are only partially complete and many minor species are not included. When we searched the literature for profile and weight equations, our primary objective was to build systems for the southern and southeastern U.S. We included species from other areas of the country as we found them; however, our search just did not find many useable systems. Our goal is to make the system as comprehensive as possible, and we request help in finding additional publications with equations that can be included in our system. Also, if you would like to make suggestions on how to improve the dll and interface, please contact us at eschultz@cfr.msstate.edu or tmatney@cfr.msstate.edu.

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