QUANTIFYING ABOVEGROUND CARBON STORAGE IN MANAGED FOREST ECOSYSTEMS IN OHIO

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ABSTRACT.—The amount of carbon sequestered was determined on managed even aged stands on sites in southeastern Ohio. Bottomland hardwood sites that consisted of sycamore (*Plantanus occidentalis*) and box elder (*Acer negundo*) were examined. The other forest types studied were monocultures of green ash (*Fraxinus pennsylvanica*), Austrian pine (*Pinus nigra*), and pitlolly pine (*Pinus rigida* × *taeda*), and five sites of white pine (*Pinus strobus*). These represented a chronosequence of ages for each forest type. There were nine .008-hectare plots located on each white pine site and three plots on each of the other sites. DBH and basal diameter were measured for all of the trees on each measurement plot. Trees were destructively sampled to determine the DBH, basal diameter, and dry weight of aboveground components (bole, crown stem, and branches and foliage) and samples were taken to determine the amount of carbon in tree components based on percent of weight. Regression analysis was used to determine the relationship between DBH or basal diameter and total carbon sequestered and subsequently applied to trees at the plot level to estimate total tree carbon per hectare. ANOVA was used to test for differences in carbon content between components and species.

Carbon is emitted into the atmosphere from both natural and anthropogenic sources. It is the emissions from anthropogenic sources that contribute to the accelerated greenhouse effect popularly called "global warming". Forestlands are capable of mitigating this effect by absorbing and storing carbon. Through forest management practices greenhouse gas emissions can be offset. Ohio forest products and energy industries (and others) are interested in the potential use of their lands for carbon sequestration. The term carbon sequestration implies the absorption and storage of carbon from the atmosphere into a long-lived terrestrial pool a medium such as a forest ecosystem.

Forests store two-thirds of terrestrial carbon in soil and biomass by absorbing carbon dioxide from the atmosphere and converting it into organic material, an equivalent of nearly 1 trillion tons (Brown et al. 1993). Of all the plant kingdom, forests provide the most long-lived storage sink in the carbon cycle tying carbon up in wood and soil accumulation for years before returning it to the atmosphere by respiration, decomposition, erosion, or burning. Native forests cover some 3,400 million hectares worldwide, with an additional 1,700 million hectares of other wooded lands. Forest plantations comprise of roughly 100 million hectares (Austin et al. 1998). Historically, forests have been a net source of atmospheric CO_2, as 80 percent of the world's original forest cover has been lost (Austin et al. 1998). Moreover, under current worldwide practices the world could lose 650 million hectares over the next 60 years, releasing up to 77 billion tons of carbon emissions in the process (Trexler and Haugen 1995). Because of these trends, afforestation, reforestation, and sustainable forest management practices become critical in creating and maintaining worldwide carbon stores. At the present time, six hectares are deforested globally for every hectare planted (Totten 1999).

Plantation forestry and sustainable management practices of natural forests will need to be a focus to offset these losses. Increased timber growth and the resulting carbon sequestration in forests can be accomplished through improved forest management practices. This includes regeneration, which involves the replanting of under-stocked forest stands (e.g., those damaged by disease, insects, or fire) and the harvest and regeneration of mature stands. Stocking control is another approach to increase timber growth by thinning stands where competition is retarding timber growth. Increasing the

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Table 1.—Descriptions of selected sites for forestry component of this study.

Landowner	Classification	Forest Type	Planted	Age (as of 2002)
MeadWestvaco	Abandoned agric. land	White pine	1995	7
			1993	9
			1991	11
			1988	14
			1985	17
AEP[1]	Marginal agric. land	Bottomland hardwoods	1997	5
			1993	9
		Pitlolly	2000	2
			1998	4
			1995	8
	Reclaimed grassland	Mixed hardwoods	2000	2
			1997	5
			1994	8
		Austrian Pine	2001	1
			1997	5
			1993	9

[1]American Electric Power Company.

production and harvesting of wood, or biofuels, for use as a fossil fuel substitute will also augment sequestration as will afforestation or the planting of trees on previously unforested land.

Accurate data for sites over time for various species do not exist or are limited for Ohio. Sites in this study were selected that represent a chronosequence of monotypic and mixed species forests that were planted for different management objectives. Trees were destructively sampled on each site and understory was sampled to determine the total aboveground carbon sequestered. These data and the subsequent analysis were used to model the sequestration potential over time. The projections will be substantiated by future measurements from these sites. The results may be used to provide a basis by which industries can measure and manage for carbon credits.

The objective of this study was to determine the amount of carbon sequestered in selected managed forests in Ohio by determining the rate of sequestration by measuring a chronosequence of forests, validating these rates by installing permanent plots to be monitored over time, and developing species specific relationship between biomass amount and carbon.

Biometric Model

Many of the experiments in this area in the past have used an allometric model (Kimble et al. 2003, Canary et al. 2000, Patenaude et al. 2003). This type of model estimates the biomass of the whole tree based on the measurement of part of the tree. The formulae that are used to make the biomass estimates are taken from other sources on other sites. The disadvantage of this model is that the results are based on data from other sources that may or not characterize the site under examination.

This project uses a biometric model. The biometric model uses data from the sites being examined to develop formulae that characterize the species on the site. The advantage of using the data from the sites under study to make estimates is that the allometric formulae designed and used in this study are definitely characteristic of the trees on the plot. Conspicuously missing from the literature are models that create their own allometric equations from biometric data for all parts of the study.

Site Selection and Description

A total of 16 study sites owned by MeadWestvaco, Corp. and American Electric Power (AEP) were selected that represent five different forest conditions in a chronosequence in southeastern Ohio. These sites were visited and selected with assistance from foresters from both of these corporate organizations. Descriptions of the selected sites for this study are listed in Table 1.

The sites selected had similar forest and soil characteristics, such as drainage, slope, etc. within the five different forest conditions selected. A chronosequence within each forest type was selected to provide a rate of carbon accumulation over time so that cumulative curve can be modeled. These sites will be monitored (measured) periodically to refine the model carbon accumulation curve for better future predictions.

Sites were selected that represent planted forest types at different stages in their development as well as historical use. The species represented are white pine (*Pinus strobus*), Austrian pine (*Pinus nigra*), green ash (*Fraxinus pennsylvanica*), pitlolly pine (*Pinus rigida* × *taeda*), and bottomland hardwoods (*Plantanus occidentalis* and *Acer negundo).* There were five *Pinus strobus* sites represented, two bottomland hardwood sites and three each of the remaining species. The *Pinus strobus* and *Pinus rigida x taeda* sites were located on abandoned agricultural land. The *Fraxinus pennsylvanica* and *Pinus nigra* sites were located on reclaimed surface-mined land, and the bottomland sites were marginal agricultural land.

Permanent square .08-hectare plots were placed on each site with at least a one-chain buffer separating plots. Within each plot a circular .008-hectare measurement plot was placed. Each tree was permanently labeled with an aluminum tag. An aluminum nail was placed at 1.4 meters above ground level on trees large enough to hold a nail to facilitate future measurement of dbh. Trees greater than or equal to 1.3 centimeters DBH within the measurement plot were measured for dbh and basal diameter. Trees less than 1.3 cm dbh were measured for height and basal diameter.

Laboratory Methods

Destructive Tree Measurements

Trees were cut at the ground line, and separated into components of bole, branches, and foliage. Large trees were cut into manageable pieces and weighed in the field to the nearest 0.05 kg. Small trees were brought back to the lab and weighed to the nearest 0.01 g.

Trees destructively sampled were taken in equal numbers from each site and in sizes to represent the range of sizes of trees in the study. The number of samples from each site was greater for the young trees because of the difficulty in destructively sampling very large trees.. The samples were taken from near the measurement plots but not on the plots so as to not disturb possible future study.

Samples were taken from all trees that represented the different tree components and weighed. In order to ensure that the samples represented the whole component of each tree, samples were taken from different parts of each. In stems, the sample consisted of pieces from the base, tip, middle, ¼ and ¾. Branches were sampled that represented a range of sizes and leaves were taken from different parts of the plant. Samples were dried in ovens for three days at a constant temperature of 60^{o}C. Samples were then reweighed after drying to determine moisture content. The subsequent moisture content value was used to determine the total dry weight of the tree and its components.

Surface samples, which includes all surface litter above the mineral soil, herbaceous and woody plants, were collected on each measurement plot from a 1.0 m^2 plot centered on the measurement plot. One sample was taken from each plot for a total of 9 per site in the white pines and 3 per site in the other sites. The total surface sample was weighed to the nearest 0.05 kg, and a grab sample was taken. This grab sample was weighed and dried for three days at 60^{o}C to determine moisture content. The percent moisture content was applied to the total surface sample to estimate the total dry weight.

Carbon Determination

At least 0.04g of sample and usually more was collected from all tree components and surface samples for the purpose of determining carbon content. This small carbon sample was randomly collected from each tree component and ground in a Wiley mill to pass a 2mm sieve. These samples were sent to the STAR laboratory at the OARDC in Wooster, Ohio.

Table 2.—Equations for predicting total aboveground tree carbon (t/ha) by age (yrs) for the five forest types examined in this study in southeastern Ohio.

Forest type	Equation[a]	R^2 x 100
Austrian pine	$C = 0.0040e^{0.9471(A)}$	99.94
Pitlolly pine	$C = 0.0582(A)^{3.2503}$	99.98
Green ash	$C = 0.0084(A)^{1.7301}$	89.47
Bottomland hardwoods	$C = 0.0024(A)^{3.9891}$	100.0
White pine	$C = 0.4340(A)^{1.8618}$	78.02

[a]C = the total carbon in metric tons/ha for only the aboveground portion of all trees, and does not include forest litter above the mineral soil, and any herbaceous and woody understory; A = the stand age in years.

Carbon analysis was run on an Elementar Americas, Inc., Vario Max Carbon Nitrogen Combustion Analyzer, with a procedure described in the international standard publication ISO10694:1995(E). The amount of carbon measured in the samples by this method was expressed in units of percent carbon by dry weight.

Analytical Methods

Analysis of variance (ANOVA) was performed on the carbon content values by tree component, using species as the source of the variation, to determine if difference existed in carbon content among species.

Tree carbon equations were derived using regression analysis relating carbon weight with BD or dbh (depending on which best fit the data). The total weight of carbon was determined by multiplying the dry weight by the percent carbon.

These equations were applied to the data from the measurement plots to estimate the total carbon on each plot. The independent variable (either basal diameter or dbh) was used to determine the amount of carbon per tree on each plot. The estimated carbon of each tree were summed for each plot, and divided by plot size to give the carbon stored in grams per hectare, and converted to metric tons.

Carbon content for the surface samples was determined using the same method as described for the destructive samples. The values for the plots on each site were averaged to determine the weight of carbon for the surface.

The total tree carbon per hectare was averaged for each site, and was added to the carbon content of surface samples to give a total value of carbon per hectare on the site. Regression analyses were performed on the data to show the relationship between total carbon per hectare and age.

All statistical analysis was performed with Minitab (Meyer and Krueger 2001) or SAS (SAS Institute 1990).

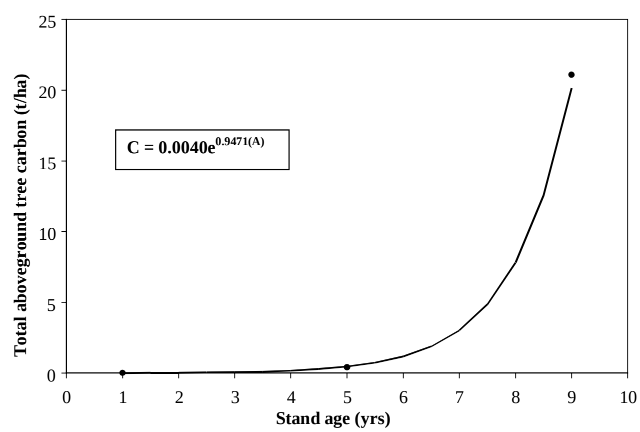

Figure 1.—Graph of total aboveground tree carbon (t/ha) versus stand age (y) for *Pinus nigra*.

Results

Total Carbon (plot)

The plot data were first considered without the surface samples examining only the total aboveground tree carbon. The equations with R^2 and standard error data are located in Table 2. The model that was used was chosen since it showed the best fit to the data by R^2 and by the fit of the predicted values against the actual values. This model was chosen over cubic, quadratic, and linear models as well as some other non-linear models. Figure 1 shows the graph of the model for Austrian pine.

Table 3.—Formulae of carbon stored by age per hectare with R^2. values with surface samples included.

Species	N	Formula	R^2 x 100
Pinus nigra	3	$C = 2.1975 A$	72.87
Pinus strobus	5	$C = 0.6990 A^{1.7286}$	80.77
Fraxinus pennsylvanica	3	$C = 0.6018 A$	24.22
Pinus taeda x rigida	3	$C = 0.7908 A^{1.9394}$	99.71
Bottomland hardwoods	2	$C = 0.0609 A^{2.5497}$	100.00

C = carbon (t); A = age (yrs)

Austrian pine, bottomland hardwood, and pitlolly pine sites showed a very strong reliability with R^2 values around 100%. The green ash sites showed a somewhat less but still fairly strong correlation (89.47%). The R^2 of 78.02% for white pine suggests a weaker reliability but still high enough to suggest a good fit.

Analyses were attempted using individual plot data as opposed to average plot data to determine if this would produce a better fit. The data were much less reliable for every species and is not reported here.

Table 3 shows the formulae for the models of carbon sequestered over time per hectare by site composition with surface samples considered. Bottomland hardwoods and *Pinus taeda x rigida* show a very strong reliability (R^2 around 100%). *Pinus strobus* has a reasonable level of reliability (R^2 = 72.87). *Pinus nigra* and *Fraxinus pennsylvanica* were better characterized by a linear regression. *Fraxinus* had a very unreliable fit (R^2 = 24.22). The *Pinus nigra* and more especially the *Fraxinus pennsylvanica* were largely influenced by surface samples in their total aboveground carbon. This is why the models without surface samples are more reliable for these forest types.

Nonlinear formulae of this form:

$$C = b_1 * \exp(-b_2 * \exp(b_3 * A))$$

were attempted to find if these would yield better results than those used in the study. The formula for *Pinus strobus* without surface samples was:

$$C = 84.2505 * \exp(-0.000016 * \exp(4.4878 * A))$$

and with surface samples:

$$C = 93.9602 * \exp(-0.000043 * \exp(4.0898 * A))$$

and for *Fraxinus pennsylvanica* without surface samples:

$$C = 1.7801 * \exp(-0.0173 * \exp(1.0209 * A))$$

with C representing carbon and A representing age. The resulting R^2 values were 84.08%, 84.20%, and 50.61%. These data also did not show as good a fit of the predicted values to the residuals. This is not an improvement on the models used in this section.

The graphs in this paper that were not linear showed a convex form. This is similar to the findings of Law et al. (2003), Pussinen et al. (2002), and Dieter and Elsasser (2002). The trees show a convex growth at the beginning of the curve followed by a concave shape toward the end. All of the ages in this study are in the range of the early part of these curves.

The total carbon per plot by species and land classification is shown in table 4. There are striking differences in C sequestered by species and land type. Austrian pine at age 9 stored much more C that green ash on the same type of sites at age 8 (30 and 4 t/ha respectively). Bottomland hardwoods on bottomland sites stored much more carbon at age 4 than pitlolly pine at age 5 (11 and 3.1 g/ha). White pine on abandoned agriculture sites changed dramatically in carbon storage between age 11 and 14 (24 and 89 t/ha).

Table 4.—Total carbon per plot (t/ha) by species and land classification.

Classification	Forest Type	Age	Total C plot (t/ha)	C w/o litter (t/ha)
Abandoned agric. land	White pine	7	26	22
		9	20	15
		11	24	19
		14	89	79
		17	89	81
Marginal agric. land	Bottomland	5	3.1	0.90
	hardwoods	9	19	18
	Pitlolly pine	2	3.3	0.75
		4	11	5.6
		8	28	24
Reclaimed grassland	Green Ash	2	3.9	0.011
		5	3.2	0.20
		8	4.0	0.22
	Austrian Pine	1	3.2	0.014
		5	3.3	0.39
		9	30	27

[1]American Electric Power Company.

Table 5.—Analysis of variance statistics on the percent carbon based on dry weight by tree component. Species was the source of variation used in the analysis.

Tree component	N	Mean carbon (% of dry weight)	F-statistic	Prob>F
Bole	73	0.4950	99.65	0.0001
Branches	67	0.4994	88.32	0.0010
Foliage	73	0.5024	112.17	0.0010

Table 6.—Carbon content (percent of dry weight) by species for tree components.

	Carbon Content[1] (fraction of dry weight)							
	Bole[2]		Branch		Foliage		Branches and Foliage	
Species	N	mean	N	Mean	N	Mean	N	mean
Pinus taeda x rigida	14	0.5110 A	14	0.5121 A	14	0.5204 A	14	0.5158 A
Pinus nigra	20	0.5087 A	20	0.5161 A	20	0.5131 AB	20	0.5146 A
Pinus strobus	12	0.5072 A	6	0.5143 A	12	0.5192 B	12	0.5151 A
Plantanus occidentalis	8	0.4741 B	8	0.4797 B	8	0.4969 C	8	0.4883 B
Acer negundo	7	0.4736 B	7	0.4797 B	7	0.4613 D	7	0.4705 C
Fraxinus pennsylvanica	12	0.4679 B	12	0.4739 B	12	0.4746 E	12	0.4742 D

[1]Values followed by the same letters down columns are not significantly different at the p = 0.05 level, Duncan's multiple rage test.
[2]The bole is defined as the woody component from the ground to the tip, minus branches.

Carbon Content by Species

Table 5 displays the ANOVA statistics performed on the carbon percent by tree component. The model statistics indicated there were significant differences in carbon content among species. Duncan's new multiple range test was performed to determine differences in carbon content between species by tree component (Table 6).

As is shown in the Table 6, the carbon content for the bole is statistically similar among hardwoods and among pines but these values are statistically different between pine and hardwood species groups. The carbon percentages for hardwoods average 47% while the pines average 51%.

Greater variability was present in the foliage (Table 6). *Pinus taeda x rigida* is similar to *Pinus rigida* but different from *Pinus strobus*. Even though Duncan's test shows this difference, it may be an artifact of

Table 7.—Equations for predicting total aboveground tree carbon (C, g) for seedlings and saplings in southeastern Ohio using basal diameter (BD, cm) or diameter at breast height (DBH, cm).

Species	N	Prediction equation	R^2 x 100
Acer negundo	7	$C = 8.1484(BD^{2.7219})$	99.48
Fraxinus pennsylvanica	12	$C = 10.9910(BD^{2.6685})$	96.62
Platanus occidentalis	8	$C = 10.1620(BD^{2.5998})$	99.48
Pinus nigra	20	$C = 9.5266(BD^{2.8408})$	99.02
Pinus taeda x rigida	14	$C = 10.5800(BD^{2.8604})$	98.26
Pinus strobus	12	$C = 167.4000(DBH^{1.9167})$	93.74

the data due to small sample sizes and greater variability measured in foliage. The hardwoods are significantly different from the pines and from each other. *Plantanus occidentalis*, *Fraxinus pennsylvanica*, and *Acer negundo* have percent carbon values based on dry weight of 49.7%, 47.5%, and 46.1% respectively. These values for hardwoods are lower than those observed for pines.

When considering the branches and foliage together (Table 6), the pine group together with similar values (51.6%, 51.5%, and 51.5%), *Plantanus occidentalis* stands alone (48.8%), and the other hardwoods group together (47.4% and 47.1%).

Many of the studies in the literature use one standard percentage of carbon for all trees. For many the value is 50% (Nowak and Crane 2002, Brack 2002, Kimble et al 2003, Makundi et al 1995, Dieter and Elsasser 2002), with one at 45% (Nowak 1993) and one at 46% (Patenaude et al 2003). Canary et al. (2000) calculated the values for fir and found a range of 48.1 % to 54.6% with an average of 51.2%. All of these values seem to be consistent with the values determined by this project. The values calculated for hardwoods around 47% and pines around 52% are very close to the values of Canary et al. (2000) and not far from standardized values of 45% and 50% for all species. The finding of an average carbon percent by Canary et al. (2000) of 51.2% for fir goes to further the idea that conifers have a similar carbon content as one another as that values is likely not significantly different than the values found in this study for conifers.

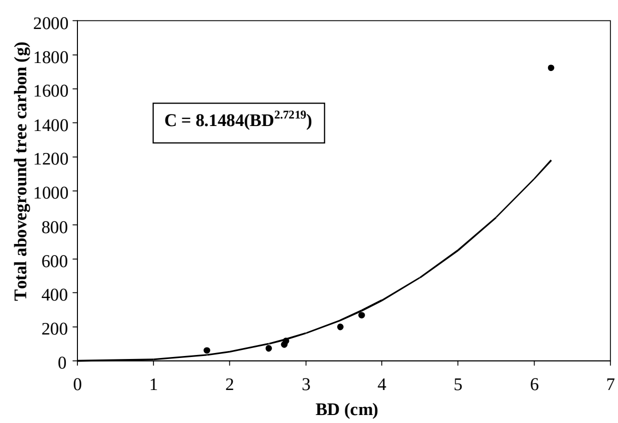

Figure 2.—Graph of total aboveground tree carbon (g) versus basal diameter (g) for *Acer negundo*.

Carbon Equations (individual tree)

The data for the individual tree carbon models had very good R^2 values ranging from with 93.74% to 99.48% (Table 7). A comparison of the R^2 values and predicted versus residual plots, indicate individual tree carbon models shows a good fit of data per species. All of the models show a high reliability ($R^2 > 93\%$).

Figure 2 shows the graph for the model of the carbon data for *Acer negundo*. Carbon storage begins to increase dramatically after seedlings become established and more rapid growth occurs. For example, the ratio of carbon (g) to tree size (BD) increases from about 30:1 to 180:1 for *Fraxinus pennsylvanica*.

Discussion

The greatest contribution of this paper is the use of equations of carbon storage by age. This model is only valid for plantations since it requires an even age. The high R^2 (78-100) of these formulae suggests that this is a valid option for plantations. This is significant since equations of stand C by age could present a potential shortcut in estimating plantation C storage. This would replace having to measure individual trees or compare inventories to carbon equations for individual trees.

The results from the comparison of land use and species to carbon storage are important (Table 4). The results suggest that species types should be selected that have the best success on the particular site that is being used. Management options should consider this when managing for optimal carbon sequestration. For example, Austrian pine had much better success than green ash on reclaimed mine sites.

Empirical models developed are useful for predicting aboveground biomass in the carbon pool. The equations predicting carbon per tree from basal diameter are all valid for southern Ohio for several species (R^2 x 100 > 88). This high degree of reliability shows that these models can be used in place of destructive sampling in future studies. The equations developed in this study to relate C to basal diameter or DBH are preferable on these sites to equations drawn from the literature since variation may exist between the stands from which the literature values are drawn and the stands under study in this paper.

The differences in carbon content for different species pose questions as to what in the make-up of the trees causes them to have these differences. Pines have a carbon percentage around 52%, while hardwoods have a carbon percentage around 48%. A study in the biochemistry of these species may produce interesting findings in how different species function.

Site conditions and spacing are factors that may be worth considering in future studies. These may have an effect on the carbon sequestered by particular sites. More replications and a broader range of ages would help support the data.

A useful part of this study is the allometric equations derived from the destructive samples. Assuming these values to be statistically significant, which they seem to be, at least for the range of values tested, in most cases, these would make destructive sampling of these species not necessary in future studies of these species unless as a check.

On the whole, this study proved very effective. The results were in general very reliable. The objective of determining the carbon sequestered by species was met with a high degree of reliability. The models should prove useful in future studies.

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