CARBON STORAGE BY UTILITY-COMPATIBLE TREES

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Abstract. Urban trees can favorably affect factors underlying global warming by storing carbon and by reducing energy needed for cooling and heating buildings. To estimate the amount of carbon stored by smaller types of urban trees, excluding leaves and roots, standardized measurements were taken to determine wood density, wood volume, and dry weight of selected samples of *Amelanchier, Malus, Pyrus calleryana*, and *Syringa reticulata* cultivars. Wood density as defined by specific weight ranged from 0.53 to 0.64 g/cm^3 for all genera. Densities at two upper trunk positions were significantly different from those at the base. The wood density of *Syringa reticulata* was significantly less than the other genera. Regression analyses of wood weight based on height and diameter of trees up to 12 cm (4.7 in.) dbh indicated a linear relationship in *Amelanchier*, but curvilinear (not linear) equations explained more of the variation in *Malus* and *Pyrus*. Smaller trees, those 2.3 to 4.9 cm dbh, typically stored between 2.1 and 2.3 kg of carbon in trunks and branches; trees between 5.0 and 7.9 cm stored between 8.4 and 15.1 kg, and trees larger than 8.0 cm up to 11.7 cm stored between 24.5 and 37.5 kg of carbon. The narrow-crowned *Pyrus calleryana* 'Capital' stored considerably lower amounts of carbon than the other *Pyrus calleryana* cultivars. These estimates may be increased by 22% to add carbon stored in roots, according to other studies.

Key Words. Carbon storage; urban trees; carbon sequestration; global warming; carbon dioxide removal; wood density; wood volume; *Amelanchier; Malus; Pyrus calleryana; Syringa reticulata.*

With the growing importance of urban forestry, new ways are being discovered by which trees benefit the environment, including amelioration of climate and energy conservation through the proper placement and management of trees within communities. Because increasing levels of CO_2 in the atmosphere may cause global warming, policy makers are striving to find ways to reduce CO_2. Trees can store large amounts of carbon; therefore, forests play an active role in sequestering carbon (Sedjo 1989). Urban forests in the United States are estimated to store between 400 and 900 million tons of carbon (Coder 1993; McPherson 1994; Nowak 1994).

Most equations that predict carbon storage have been calculated from forest trees and are of questionable accuracy for urban trees; some of these estimates exclude small trees less than 12.7 cm (5.0 in.) dbh. Annual carbon sequestration rates are up to 90 times greater for healthy large trees as compared to healthy small trees, such as those commonly planted in urban areas. Open-grown trees typically are shorter but often have larger crowns with more branches than forest grown trees (Nowak 1994). Preliminary indications from Nowak are that biomass equations derived from forest stands overestimate the biomass of open-grown urban trees by a factor of 1.25 (Nowak 1994). The differences between effects of urban and natural environments on growth forms of trees, and how trees are managed and sustained in these contrasting environments, are possible reasons for discrepancies when forest equations are applied to urban trees. Urban trees usually are transplanted from nurseries and managed for aesthetics, so that pruning removes stored carbon. Trees in forests often are naturally regenerated and managed for timber production. Trees in urban environments are subjected to different kinds of stressful environments, such as soils altered by construction; pollution of soils and air; and space limited by buildings, sidewalks, and overhead wires. The urban environment has a vastly different microclimate from that of a forest. Differences among species in growth characteristics also may explain why estimates of carbon storage can vary among trees of the same diameter (Fetcher et. al 1988; Wullschleger et al. 1992; Nowak 1994).

The estimates of this study are intended to be useful for participants in the U.S. Department of Energy's Climate Challenge Program, which is a cooperative, voluntary effort between the Department of Energy and the nation's electric utilities to reduce, avoid, or sequester greenhouse gas emissions. Utilities need more accurate data to estimate and report the amount of carbon stored in urban trees, in order to qualify for carbon credits. The results will also be useful in quantifying ecological and economic benefits of urban forests and will contribute to the development of urban forest effects models (Nowak and Crane, in press).

OBJECTIVES

The primary objective of this study is to develop accurate equations to predict carbon storage for smaller trees commonly grown in confined spaces and under utility lines, by defining the relationships among diameter, height, wood volume, and dry weights as a basis for carbon estimates. By comparing variations among genera and cultivars, the study examines the specificity desirable for carbon estimates and formulates results for convenience of practical applications.

METHODS

Study Sites and Species

Wood samples and tree measurements were collected from May through July 1998 at three nurseries. Two nurseries are located in central Pennsylvania, U.S. (PenCor Nursery near Pleasant Gap, and Nittany Trees near Zion); the third, Lake County Nursery, is near Perry in northeastern Ohio. The study trees were randomly selected within blocks of trees from which many had been sold, so that some sizes were larger than those typically planted, up to 11.7 cm (4.6 in.) dbh and 8.7 m (28.6 ft) in height (Table 1). At each nursery, there were one to three cultivars in each genus except for *Syringa reticulata*, which was available only at PenCor Nursery (Johnson 1999).

The species included in the study represent trees commonly planted as street trees, especially trees growing under utility lines. Four genera of trees with one to seven cultivars each are represented in the study. From each nursery, five trees of each cultivar were selected, for a total of 90 trees. There were three cultivars of *Amelanchier*: *Amelanchier* × *grandiflora* Cumulus® (at two locations), *Amelanchier canadensis* Tradition®, and *Amelanchier lævis* 'Snowcloud'; six cultivars of *Pyrus calleryana:* Aristocrat™, 'Capital', 'Cleveland Select', 'Redspire', Stone Hill', and Valiant®; seven cultivars of crabapple (*Malus*): Centurion®, Harvest Gold®, 'Ormiston Roy', 'Robinson', 'Snowdrift', 'Strawberry Parfait', and × *floribunda* (Japanese flowering crabapple); and *Syringa reticulata* 'Ivory Silk'. In three of the four genera, trees ranged from 2.3 to 11.7 cm (1.0 to 4.6 in.) dbh and 3.1 to 8.7 m (10.2 to 28.6 ft) in height. *Syringa reticulata* had a smaller range of dbh and height.

Table 1. Range of heights and diameters of trees sampled in four genera: *Amelanchier, Pyrus, Malus,* and *Syringa*.

Genus	No. of cultivars	Source	Range of heights (m)	Range of dbh (cm)
Amelanchier	3	L, P, N	3.99–7.47	2.31–9.40
Malus	7	L, P, N	3.11–7.53	2.89–11.68
Pyrus calleryana	6	L, P, N	3.14–8.72	3.98–10.99
Syringa reticulata	1	P	4.42–5.00	5.08–7.36

(L) Lake County Nursery
(P) PenCor Nursery
(N) Nittany Tree Nursery

Data Collection

A subsampling technique proposed by Valentine et al. (1984) for rural forest stands was used to estimate the biomass in the branches and trunk of each tree. This approach uses importance sampling to select trunk discs, thus eliminating the cumbersome need to section and weigh the entire trunk. Randomized branch sampling was used as an alternative to weighing all branches. Because the method is statistically based to produce unbiased estimates, it should be transferable to open-grown deciduous trees that have not received recent or significant amounts of pruning, such as those in urban landscapes (Peper and McPherson 1998). Only the trunk and branches of each tree were sampled. Leaves were excluded because they are shed each year and account for only a small proportion of total tree weight. Roots were excluded because of time constraints, though they certainly are significant in the total carbon storage within a tree. Although belowground biomass oftentimes is excluded from whole tree calculations, it is of great importance and accounts for about 22% of the total biomass (Nowak 1994).

Subsampling Method for Woody Biomass

Before samples were cut from a tree, its dbh and height were measured. Soil and any suckers around the base of each tree were removed so that the tree could be cut at ground level. The biomass of the trunk and branches was estimated from measurements and wood samples along a selected path (see appendix for details). Sequential, internodal segments of the path extending from the base to the terminal point of a branch or the trunk were randomly selected at every node, where alternative pathways could proceed along the trunk or along one or more branches. Branches less than 2 cm in caliper were excluded from the path. Clusters of branches were grouped together and defined as a node if they were separated by less than 4 cm. Using the formula of Valentine et al. (1984), the next segment of a path was determined by comparing a random number, which was computer generated, and the selection probability of each alternative path calculated from the measurements of trunk or branch diameter and length.

At the uppermost path-node where at least two branches, or a trunk and one branch, both exceeded 2 cm in caliper, the selected branch or trunk was cut off at the end of the path. This terminal path branch was oven-dried and weighed. The unconditional probability of reaching the path branch and the dry weight of the branch were used in an equation (Valentine et al. 1984) to determine the inflated weight of all branches. Branches along all possible paths that were less than 2 cm in caliper were cut off and weighed together. The combined weight of these branches, termed epicormic branches, was included in the final total weight of the tree.

The dry weight of the trunk was calculated from a 4 cm thick disc cut at a randomly selected location along the path. Although the discs of large trees should be quite thick to reduce error, perhaps 10 cm or more, this was reduced due to the small size of the trees. Measurements of trunk diameters and lengths were taken along the path where nodes existed or large changes in taper occurred, such as above the butt flare. These measurements were incorporated into a selection probability formula to determine the position and locations where discs were to be cut. Cuts were made 2 cm above and 2 cm below this point.

Several other discs were selected from the path at predetermined positions, but they were not used to estimate the weight of the tree. Three discs were removed from the butt flare of the felled tree, one at the base, and two others extending 4 to 8 cm and 8 to 12 cm from the base. Two additional discs were taken at intervals, one at the highest point measured in full meters from 12 cm above the base, and one midway between these two points. The additional discs, along with the one chosen using the trunk weight equation, were used to establish a relationship between trunk diameter and density.

The density dry weights of all discs (dry weight per unit volume) were determined by submerging each disc in a container of water, measuring the amount of water displaced, and drying to a constant weight in an oven at 105°C ± 3°C. An estimate of the total dry weight of the trunk was determined from the inflated weight of the selected oven-dried disc of each tree (Valentine et al. 1984).

The total aboveground weight was estimated using the inflated dry weights of the measured components (see appendix). The dry weight was then multiplied by 0.5 to determine the weight of carbon in the tree. This can then be multiplied by a factor of 3.67 (the ratio of the atomic weights of CO_2 to C) to determine the weight of carbon dioxide that had been sequestered (Nowak 1994).

Data Analysis

The amount of carbon stored has a direct relationship to wood density. Regression analyses were used to determine the relationship of trunk diameter to density, and therefore to what extent diameter of sample discs may influence estimated weight of the tree. An analysis of variance (Minitab General Linear Model) was used to analyze variation among five trunk positions and four genera.

After calculating carbon stored in each tree, height-to-diameter relationships in all genera were plotted to determine if outlying values occurred (Johnson 1999). Linear and curvilinear regression analyses for *Amelanchier*, *Pyrus calleryana*, and *Malus* were then calculated to determine the relationship of the amount of carbon stored to dbh and height. Regression equations took the form of $y = ax^b$, where y = carbon storage, $x = \text{dbh}^2 * \text{ht}$, and b = coefficient. A regression analysis was not performed for *Syringa reticulata* because a sample size of five was too limited. *Pyrus calleryana* 'Capital' was excluded from two of the regression analyses because it was atypical, as explained in the results.

Means and ranges of carbon estimates were determined for three tree sizes by extracting all data points that fell within a dbh range and calculating the average carbon stored. Percentage of carbon stored in the trunk was determined by dividing the estimated amount of carbon stored in the trunk, after inflation, by the estimated total amount of carbon stored.

Comparison to Other Estimates

The only direct comparison to data obtained in this study is with the data of Nowak (1994). However, indirect comparisons were made with biomass estimates from Tritton and Hornbeck (1982). Data for pin cherry was used, due to its smaller size in growth habit as compared to the other hardwoods, and also general hardwoods and "puckerbrush" (mixed brush species in New England). These data from the literature consisted of estimates for trees 5.0 and 10.0 cm dbh and are divided between trunk and branch components. For comparisons with our data, average biomass per tree was calculated for trees 2.5 to 7.5 cm dbh and 7.5 to 12.5 cm dbh. Regression equations of the form $y = ax^b$ used to predict biomass (y) of our trees from dbh^2 * ht (x) were compared to biomass estimates in Tritton and Hornbeck (1982).

RESULTS

Trunk Densities

There were significant differences in densities of discs, ranging between 0.53 and 0.63 g/cm^3 based on position in the tree and on genus (Table 2). Densities decreased from the bottom of the tree to the top in all genera. Only the upper two positions differed from the bottom three taken from the base flare of the tree (Table 2). *Amelanchier* was denser, while *Syringa reticulata* was the least dense of the four genera tested.

Carbon Estimates

The total amount of carbon stored in a tree increased with dbh and height, especially as diameter increased above 5 cm (Figures 1 and 2). Trees less than 6 cm dbh stored relatively low amounts of carbon with small amounts of variability, while trees larger and up to 12 cm stored more carbon and were highly variable in all genera except *Amelanchier*. The relationship with the best fit for all trees in the four genera combined was allometric ($y = ax^b$), i.e., curvilinear, where y = kg carbon and x = centimeters dbh^2 * ht in meters. The resulting coefficient of determination was a 0.707, i.e., 71% of the variation in carbon estimates was accounted for. The only apparent difference among cultivars was that 'Capital' differed from other pear cultivars (in Figure 1, points above 9 cm dbh). When 'Capital' was omitted from the regression, 76% of the variation was accounted for by the equation $y = 0.0166x^{1.1763}$.

Table 2. Mean density of trunk discs sampled at five positions in trees of *Amelanchier, Pyrus calleryana, Malus,* and *Syringa reticulata.*

Genus	Mean density for genus	Position	Mean density for position
Amelanchier	0.630 a*	5, at top	0.5647 a
Malus	0.590 a,b	4	0.5715 a
Pyrus calleryana	0.593 a,b	3	0.5951 b
Syringa reticulata	0.530 c	2	0.6005 b
		1, at base	0.5952 b

*Values followed by the same letter do not differ significantly at 0.05% level.

Allometric regression analyses (Figures 3 through 5) indicated that *Malus* stored more carbon than other genera, and both *Malus* and *Pyrus calleryana* were more variable than *Amelanchier*; therefore, the three should be treated separately. The regression equation that best fits the relationship between y = kg carbon and x = centimeters dbh^2 * ht in meters for the *Amelanchier* cultivars was linear: $y = 0.0424x - 0.5946$, accounting for 89% of the variation. Less of the variation in *Malus* and *Pyrus calleryana* was accounted for by linear equations, 40% and 20%, respectively. With the removal of the 'Capital' cultivar, variation accounted for in *Pyrus calleryana* increased to 60% (Johnson 1999).

Curvilinear equations better explained the carbon stored within *Malus* and *Pyrus* associated with $x = dbh^2$ * ht. This equation in *Malus* was: $y = 0.0217x^{1.1574}$, accounting for 74% of the variation (Figure 4). The equation for *Pyrus calleryana* was $y = 0.0155x^{1.117}$, accounting for 73% (Johnson 1999). However, with the exclusion of the 'Capital' cultivar, the equation becomes $y = 0.0029x^{1.4607}$, accounting for 89% (Figure 5).

The means and ranges of carbon values in diameter classes for three genera increased greatly as trees exceeded 5 cm in dbh (Table 3). Average carbon stored by individual trees was 2.2 kg (5.0 lb) for a tree less than 5 cm (2 in.) dbh, and it exceeded 25 kg (55 lb) for a tree greater than 8 cm (3 in.) dbh.

In smaller trees less than 5 cm dbh, more than 80% of the carbon was stored in the trunks of *Amelanchier* and *Pyrus* cultivars, compared to 65% in

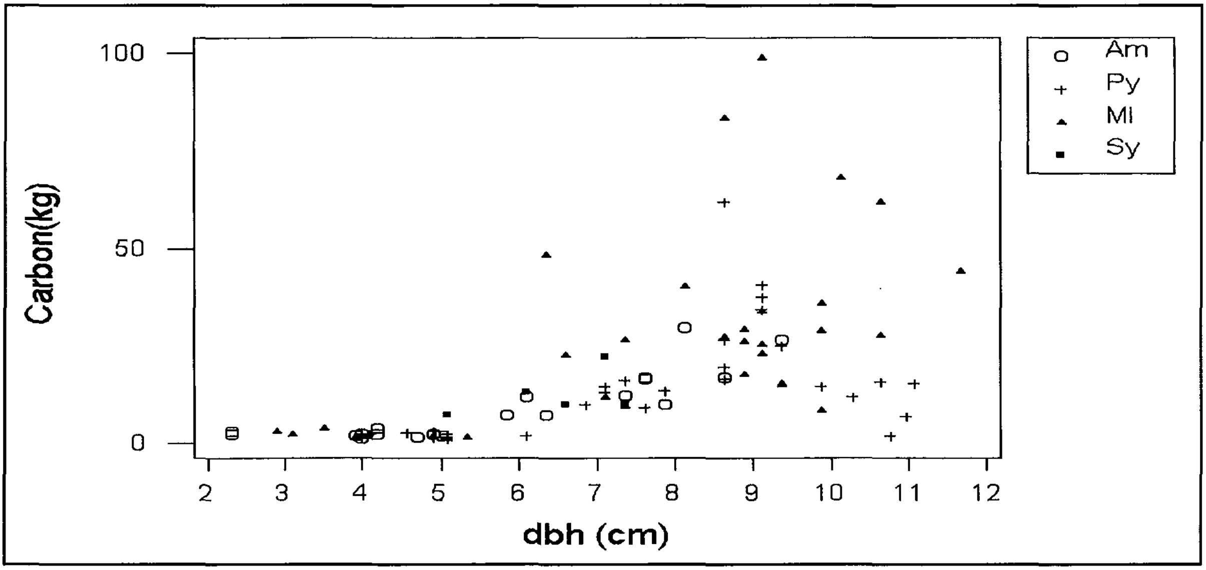

Figure 1. Carbon (kg) stored in individual trees of *Amelanchier* (Am), *Pyrus calleryana* (Py), *Malus* (Ml), and *Syringa reticulata* (Sy), plotted by diameter (dbh). Py points beyond 9 cm dbh are 'Capital' cultivar.

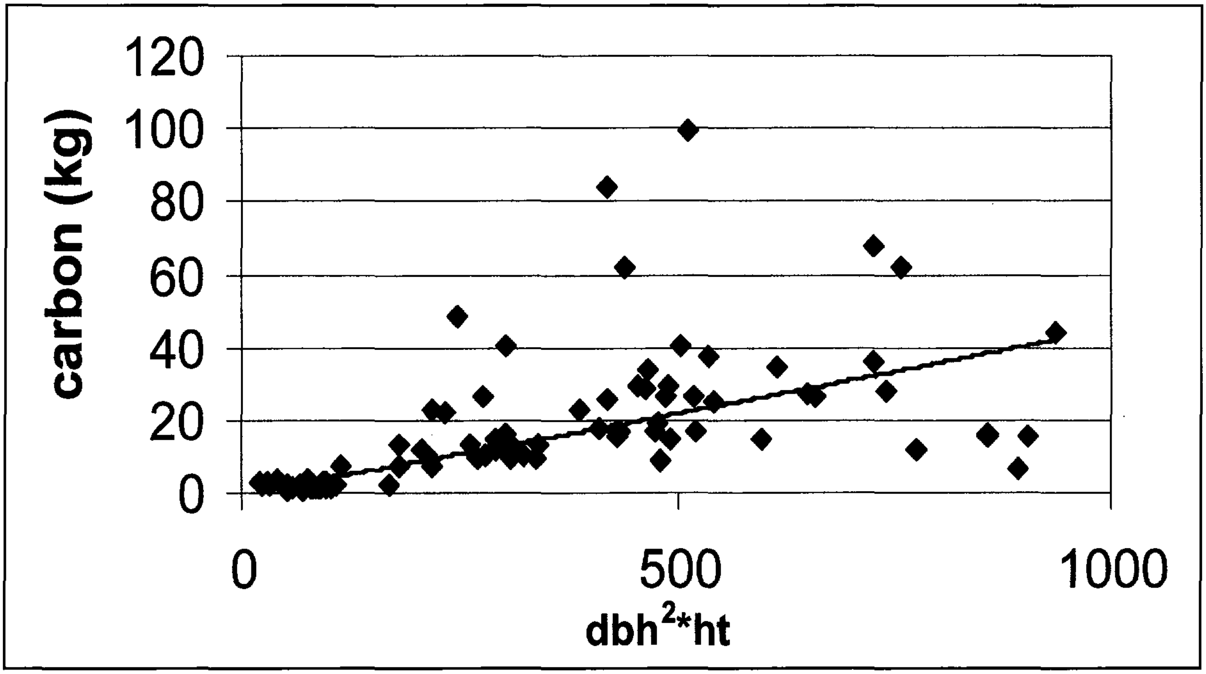

Figure 2. Carbon stored in *Amelanchier, Pyrus calleryana, Malus,* and *Syringa reticulata* cultivars according to dbh^2 * ht. Allometric regression equation is $y = 0.0272x^{1.0718}$, $R^2 = 0.707$ or 71%.

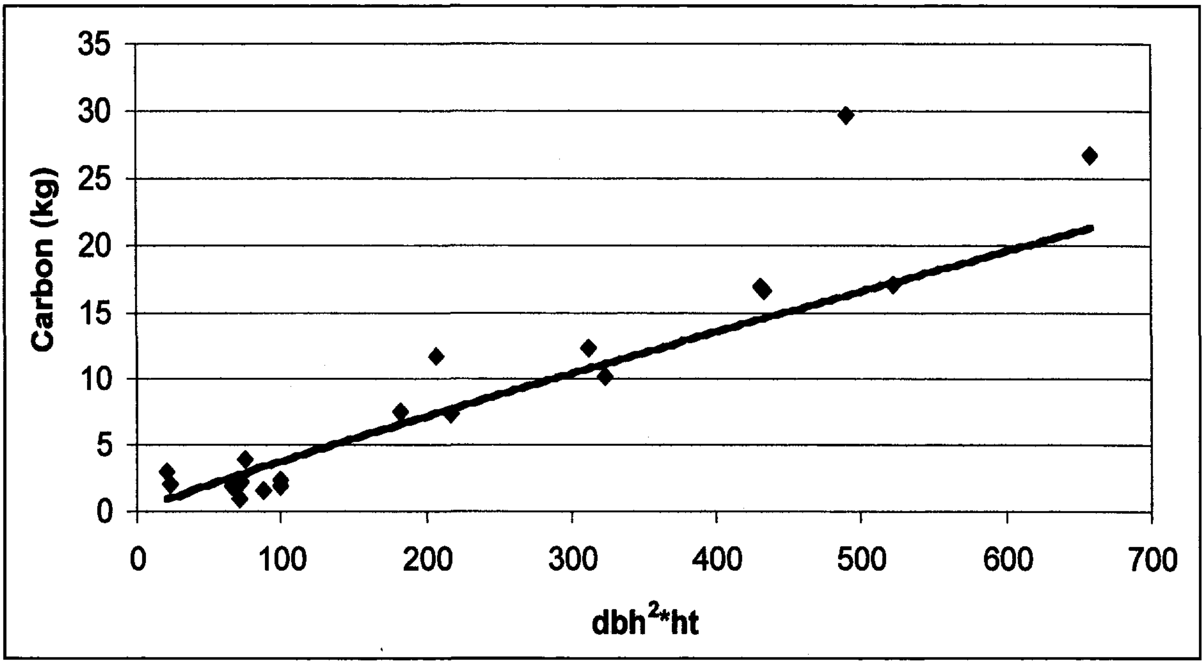

Figure 3. Carbon stored by *Amelanchier* cultivars. Allometric regression equation is $y = 0.0538x^{0.9222}$; R^2 = 0.751 or 75%.

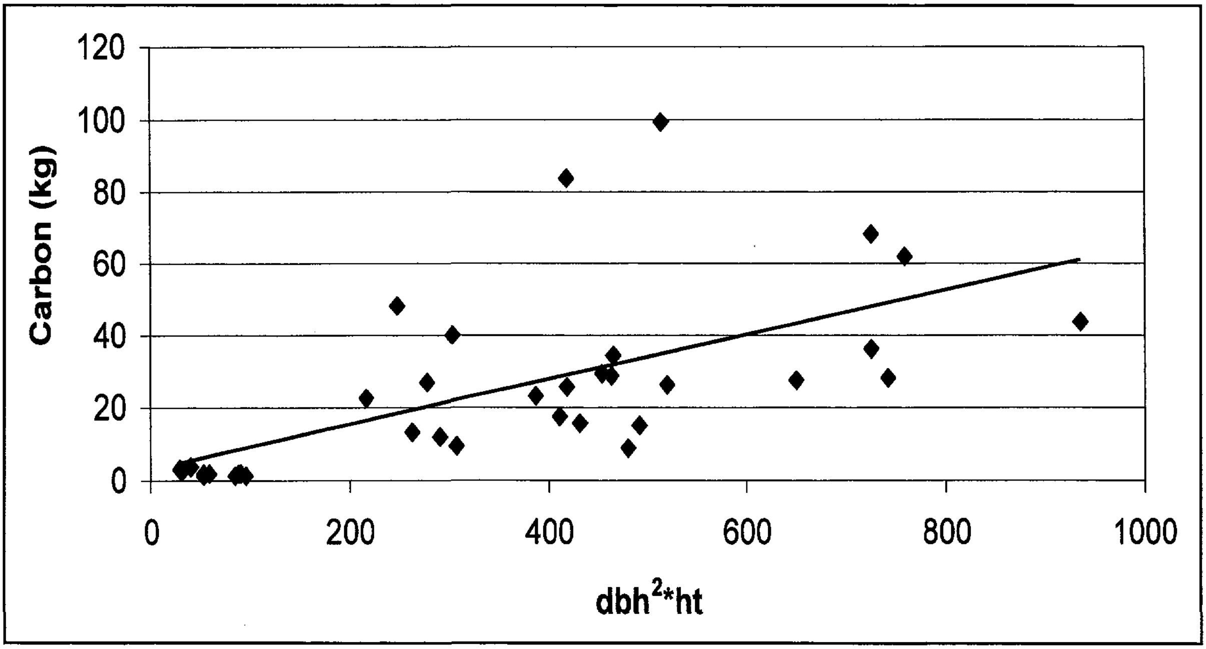

Figure 4. Carbon stored by *Malus* cultivars. Allometric regression equation is $y = 0.0217x^{1.1574}$; R^2 = 0.7425 or 74%.

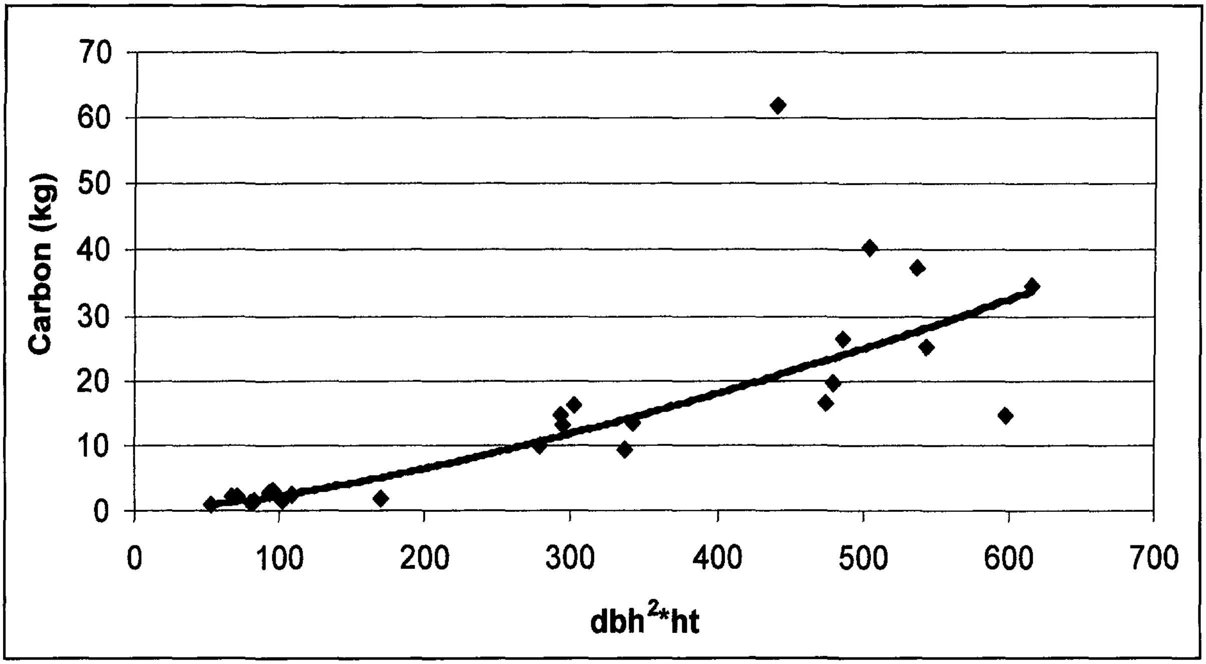

Figure 5. Carbon stored by *Pyrus calleryana* cultivars (excluding 'Capital'). Allometric regression equation is $y = 0.0029x^{1.4607}$, $R^2 = 0.8877$ or 89%.

Malus (Table 3). In larger trees of all species (5 to12 cm dbh), the percentage of carbon in trunks compared to branches decreased, especially in *Malus*, where it decreased below 40%.

When compared to biomass estimates in the literature (Tritton and Hornbeck 1982), allometric regression equation coefficients for the study data were lower, and therefore biomass volumes and regression lines were lower (Table 4 and Figure 6). The equation for *Quercus prinus* (Figure 6) is shown because it was derived from the lowest biomass of trunk plus branches compared to others cited in the literature on forest trees.

Table 3. Means and ranges of carbon storage estimates, and percentage stored in trunks, for selected dbh ranges of *Amelanchier*, *Pyrus calleryana* (excluding 'Capital'), and *Malus*.

Dbh (cm)	n	Mean (kg)	Range (kg)	% of carbon in trunk
Amelanchier				
2.3–4.9	9	2.2	1.0–3.8	82
5.0–7.9	8	10.5	1.9–16.9	66
8.1–9.4	3	24.5	17.1–29.7	45
Pyrus calleryana				
3.9–4.9	6	2.1	1.0–3.1	86
5.1–7.4	10	8.4	1.2–16.2	65
8.6–11.1	14	25.5	7.0–62.0	50
Malus				
2.8–4.8	7	2.3	1.4–3.9	65
5.1–7.4	9	15.1	1.2–48.3	33
8.6–11.7	19	37.5	8.6–99.3	39

DISCUSSION

Evaluation of Methods

The sampling method developed by Valentine et al. (1984) using rural forest trees has not been used before with nursery-grown trees, and seldom with biomass estimates of open-grown trees. Peper and McPherson (1998) used the method and found that woody and total aboveground biomass for six open-grown mulberry trees and two Chisos cherry trees revealed no significant difference from the actual weight of the same trees.

In our study, we examined the possibility that differences in wood density are associated with trunk positions or diameters of discs. There were only minor decreases in density at smaller diameters in the two upper positions, and these were consistent in all genera. The lower densities in these cases could not account for the unexplained outlier values for high carbon storage.

Table 4. Biomass estimates (kg dry weight in trunk and branches) of this study compared to others based on trees of selected dbh (2.5 to 7.5 cm in this study compared to 5.0 cm in Tritton and Hornbeck; and 7.5 to 12.5 compared to 10.0 cm).

		Dbh	
Reference	Component	5.0 cm	10.0 cm
General hardwoods			
Tritton and Hornbeck, 1982	Branch:	0.5	3.2
(Kenerson & Bartholomew, 1977)	Trunk:	5.1	27.3
Tritton and Hornbeck, 1982	Branch:	0.9	2.6
(Ribe, 1973)	Trunk:	4.1	23.8
***Prunus pensylvanica* (Pin cherry)**			
Tritton and Hornbeck, 1982	Branch:	0.9	3.2
(Ribe, 1973)	Trunk:	5.4	18.6
Amelanchier	Branch:	3.0	11.0
This study	Trunk:	4.3	10.0
Pyrus calleryana	Branch:	2.1	10.1
This study	Trunk:	3.0	11.0
Malus	Branch:	5.3	21.7
This study	Trunk:	4.5	14.2

Influencing Factors

Tree growth and biomass accumulations are highly influenced by genetics, climate, soil, moisture, alterations in physiological functions, and competition. Since all trees in this study were grown in a nursery, competition can by discounted as a contributing factor due to standard spacing. However, soil conditions and climate may have influenced the estimates because some trees of the same genus were grown in three different locations (Johnson 1999), thus extending the applicability of the results. Another variable not taken into consideration is the effect that pruning may have had on total accumulation, as nursery-grown trees typically are pruned in their early years to ensure proper development. Pruning that radically alters natural tree architecture can limit the application of this method in urban forests (Peper and McPherson 1998). Differences in pruning among species or nurseries also may have affected the estimates.

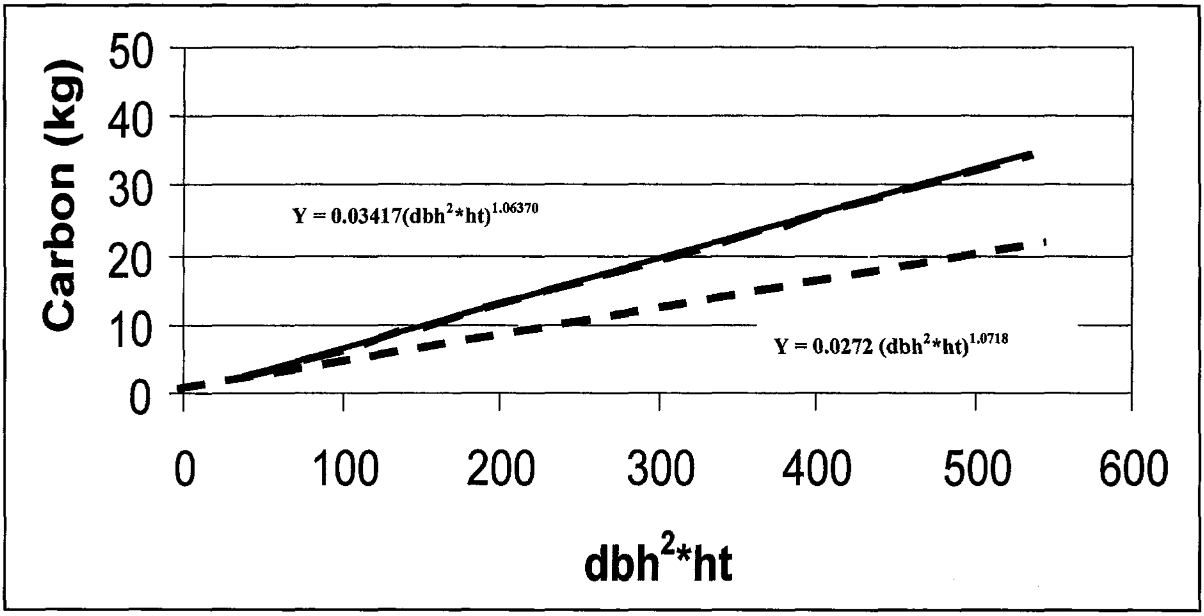

Figure 6. Allometric regression lines comparing equations from literature (solid line, 0.50 of *Quercus prinus* biomass, Tritton and Hornbeck 1982) with study data (dashed line); carbon storage plotted against $dbh^2 * ht$.

Genetic Influences

Different species of trees vary in growth form characteristics, causing estimates of carbon storage to vary. At similar diameters, the *Malus* cultivars stored considerably more carbon than two other genera, *Amelanchier* and *Pyrus* (Table 2 and Figures 3, 4, and 5). This difference could be attributed to the fact that the *Malus* cultivars had a more extensive branching habit than the other two genera. It is also possible that common pruning practices are applied differently to various species, e.g., *Pyrus calleryana* trees can be limbed up higher because they grow taller.

Much of the variability within *Pyrus calleryana* was a result of genetic influences. When *Pyrus calleryana* 'Capital' was omitted from the regression equation, the variability accounted for increased from 73% to 89%. The cultivar 'Capital' is very tall and has a slender crown, so the amount of carbon stored in its branches is lower than other trees of similar sizes. Therefore, the allometric equation for the four genera should not be used for cultivars with very slender crowns.

Height-to-diameter scatter plots of the data were similarly distributed in all genera (Johnson 1999). Only one outlier for carbon values could be explained by an unusual height-to-diameter relationship in this one *Malus* tree, indicating that other factors such as prolific branching may be responsible for a few other large carbon values noted in *Malus*.

The equations for the genera *Malus, Pyrus,* and *Amelanchier* that predict carbon storage from $dbh^2 * ht$ are appropriate only for smaller sizes of trees, less than 12 cm in diameter. Although the trees were grown in a nursery, results probably are applicable to many kinds of small trees planted in urban environments. Further studies are needed that investigate carbon storage in all sizes of urban trees.

Finding a common regression line that expresses carbon storage or biomass accumulation as a function of dbh or height appears to be possible for smaller types of trees in different genera. More than 70% of the variation was explained among 17 cultivars in 4 genera. However, due to the variation that exists within and among some genera, more exact estimates will require separate equations. Others also have attempted to develop single biomass equations that fit several species. Wiant (1979, cited in Tritton and Hornbeck 1982) found statistically significant differences between genera and concluded that species-specific equations are preferable. Nevertheless, as an initial means of determining carbon estimates for smaller types of urban trees, a single, combined curvilinear regression equation may be sufficient for multiple genera ($y = 0.0272x^{1.0718}$). Aboveground estimates calculated by this equation could be increased by 22% to include carbon stored in roots.

Comparison of Carbon Storage and Biomass Estimates

Estimates of carbon storage for trees in the study varied somewhat from those in the Chicago study by Nowak (1994), the most appropriate published estimates for comparison. However, the diameters in this study ranged from 2.0 to 11.7 cm (1.0 to 4.6 in.), whereas in the Chicago study, the diameters ranged from 0.64 cm to more than 77.0 cm and pertained to different species. Only a limited number of comparisons could be made based on available data. Nowak (1994) calculated that trees up to 7.0 cm dbh stored an average of 3.0 kg carbon, and 24 kg in trees between 8.0 and 15.0 cm dbh. In this study, trees 2.3 to 7.9 cm dbh stored 11.3 kg, and 29.2 kg for trees 8.1 to 11.7 cm dbh. The differences in carbon estimates are likely due to differences in diameter distributions.

An alternative means of comparison with other studies is to use biomass, as carbon storage is proportional to biomass. A comparison of this study to data from Tritton and Hornbeck (1982) indicates differences in the proportion of biomass accumulation in branches versus trunk of the tree, in regards to smaller and larger types of trees. In particular, the study data indicate that with increased diameters, the amount of biomass accumulation in the branches was substantially larger than those tabulated by Tritton and Hornbeck (Table 3). The most likely explanation is that forest trees tend to have smaller crowns, as opposed to those found in open-grown trees whose crowns are much wider. Ribe (1973) used puckerbrush to determine weights, while Kinerson and Bartholomew (1977) used various hardwoods. Their data were considerably different from the trees in this study, although sums of biomass in branches and trunks were similar.

CONCLUSIONS

The carbon values obtained in this study offer new data that represent many smaller types of cultivars commonly planted in urban areas, growing in differing environments at three nursery locations. The trees tested were all landscape trees of smaller sizes and varying shapes, none of which have been measured in other studies. Carbon content differed greatly among some tree species, and one difference was detected among cultivars of the same species, even with small sample sizes.

Estimates of carbon storage for smaller-sized trees appear to be consistent with limited data from other studies. Carbon storage can be expressed by diameter, or by diameter squared times height, which is a proxy for volume. Estimates and regression equations that were developed apply to most cultivars of smaller types of trees in four genera.

Trunk densities in all four genera showed small but significant differences between the lower and upper positions, but sampling position did not account for the few outlier values. However, differences in densities among genera, especially between *Syringa* and *Amelanchier*, did have a small effect on carbon storage estimates.

Variability among cultivars within a genus was detected in *Pyrus* and may have influenced estimates in *Malus*. Uncertainties occurred about *Malus* because large amounts of variability existed within the cultivars, each being represented by only five trees. The amount of carbon stored by three cultivars within the *Amelanchier* genus was relatively consistent. The carbon values obtained for the one *Syringa reticulata* cultivar were similar to other data in this study, which generally were comparable to data taken from the Chicago study for trees of the same height and diameter. Additional research is needed to further define variability within and among these four genera and others to determine the possible factors involved in the variation.

Average carbon stored in *Amelanchier*, *Pyrus*, *Malus*, and *Syringa* trees was between 2.1 and 2.3 kg for trees less than 5.0 cm dbh. Trees between 5.0 and 8.0 cm dbh had average carbon storage of 8.4 to 15.1 kg, and trees from 8.0 to 11.7 cm dbh had average carbon storage between 24.5 to 37.5 kg.

Biomass accumulations in the branch components in this study were considerably higher than in forest trees, possibly due to differences in species but more likely caused by reduced competition among open-grown trees. Although biomass accumulations in various components of trees were different in forest as compared to open-grown trees, total accumulation in trunks and branches for forest and open-grown trees were very similar. Trees grown in natural environments tend to be more confined and grow taller with narrower crowns than do trees grown in the urban environment.

Estimates of carbon storage were fairly consistent around an allometric line for all four genera, indicating the adequacy of this equation for predicting the amount of carbon storage based on diameter at breast height times height. For more precise estimates of carbon storage, species-specific equations were more appropriate. Because the study was conducted on trees less than 12 cm dbh grown under nursery conditions, further research is needed to examine these genera and others under urban conditions, and after several years of growth. Furthermore, estimates of carbon stored in the roots of urban trees and as organic matter in the soil would be very useful.

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APPENDIX

The formulas for estimating carbon content of total aboveground weight of each tree without leaves used the inflated dry weights of a randomly selected path branch, a randomly selected path disc, plus all epicormic branches taken from the base of the tree to the top. The weight per unit thickness of the disc cut at $L = \theta$ was determined to be $B(\theta)$, where L = the distance of the disc from the butt. The inflated weight per unit thickness of the disc was

$$B^*(\theta) = B(\theta) / Q_k$$

where Q_k is the unconditional selection probability of the kth segment of the path in which θ occurs (Valentine et al. 1984). The estimate of the inflated weight of the trunk and the true woody weight of the trunk is

$$w' = B^*(\theta)\, V(\lambda) / S(\theta)$$

where $V(\lambda)$ is an approximation of the quantity proportional to the inflated woody volume of the path, and $S(\theta)$ is the value of the interpolation function at the point θ (Valentine et al. 1984). The estimated total weight of the tree, b, is w' plus the inflated weight of the terminal branch and the weights of all small shoots attached to the path. Thus,

$$b = w' + b_j / Q_j + \Sigma e_k$$

where w' is the woody weight of the trunk from the butt up to the point where the path branch was severed, b_j is the weight of the terminal branch, Q_j is defined as the unconditional selection probability for the jth segment, and Σe_k is the weight of all the small shoots termed epicormic branches. The dry weight was multiplied by 0.5 to determine the weight of carbon in the tree. This can be multiplied by a factor of 3.67 (the ratio of CO_2 to C) to determine the weight of carbon dioxide that had been sequestered (Nowak 1994).

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Résumé. Les arbres urbains peuvent influencer favorablement les facteurs sous-jacents au réchauffement global en emmagasinant le carbone ainsi qu'en réduisant les besoins énergétiques pour la climatisation et le chauffage des bâtiments. Pour estimer la quantité de carbone emmagasinée par des petits arbres urbains – excluant les feuilles et les racines –, des mesures standardisées ont été prises pour déterminer la densité et le volume de bois ainsi que la masse sèche de cultivars d'*Amelanchier*, de *Malus*, de *Pyrus calleryana* et de *Syringa reticulata*. La densité du bois, définit comme la masse spécifique, s'est située entre 0,53 et 0,64 g/cm³ pour toutes les espèces. Les densités à deux endroits de la portion supérieure du tronc étaient significativement différentes de celles à la base. La densité du bois pour le *Syringa reticulata* était significativement moindre que celle des autres espèces. Des analyses de régression de la masse de bois basées sur le diamètre et la hauteur d'arbres de 12 cm et plus de DHP ont donné une relation linéaire pour l'*Amelanchier*; par contre, des équations curvilinéaires (non linéaires) expliquaient mieux les variations pour le *Malus* et le *Pyrus*. Les plus petits arbres, soient ceux de 2,3 à 4,9 cm de DHP, emmagasinent typiquement de 2,1 à 2,3 kg de carbone dans les troncs et les branches; ceux entre 5,0 à 7,9 cm emmagasinent entre 8,4 et 15,1 kg de carbone; les arbres de 8,0 à 11,7 cm emmagasinent de 24,7 à 37,5 kg de carbone. Le *Pyrus calleryana* 'Capital', de cime plus étroite, emmagasine des quantités considérablement plus faibles de carbone que les autres cultivars de cette espèce. Ces valeurs estimées peuvent être augmentées de 22% afin d'inclure le carbone stocké par les racines, et ce en accord avec d'autres études.

Zusammenfassung. Stadtbäume können durch die Speicherung von Kohlenstoff die Faktoren beeinflussen, die der globalen Erwärmung zugrunde liegen. Um die Menge an gespeichertem Kohlenstoff in kleinen Stadtbäumen ohne deren Blätter und Wurzelmasse zu messen, wurden standardisierte Messverfahren angewendet, um Holzdichte, Volumen und Trockengewicht ausgewählter Proben von *Amelanchier, Malus, Pyrus calleryana* und *Syringa reticulata* zu bestimmen. Die Holzdichte wurde definiert als spezifisches Gewicht in einer Spanne von 0,53 bis 0.64 g/cm^3 für alle Arten. Die gemessenen Dichten an zwei Stellen im oberen Stamm wichen deutlich von den Werten an der Basis ab. Die Holzdichte von *Syringa reticulata* war signifikant kleiner als bei den anderen. Regressionanalysen von Holzdichten, basierend auf Höhe und Durchmesser von Bäumen bis zu 12 cm BHD zeigten eine lineare Beziehung bei *Amelanchier*, aber die nicht linearen Ergebnisse verdeutlichen mehr die Variationen bei *Malus* und *Pyrus*. Kleinere Bäume mit 2,3 bis 4,9 cm BHD speicherten zwischen 2,1 bis 2,3 kg Kohlenstoff in Stammund Ästen, Bäume mit 5,0 bis 7,9 cm BHD speicherten 8,4 bis 15,1 kg und Bäume größer als 8,0 cm bis zu 11,7 cm BHD speicherten zwischen 24,5 und 37,5 kg Kohlenstoff. Die schmalkronige *Pyrus calleryana* „Capital" speicherte entsprechend weniger Kohlenstoff als andere *Pyrus*-Kultivare. Diese Schätzungen können anderen Studien zufolge um ca. 22 % für gespeicherten Kohlenstoff in den Wurzeln aufgestockt werden.

Resumen. Los árboles urbanos pueden afectar favorablemente los factores responsables del calentamiento global mediante el almacenamiento de carbono y por la reducción de la energía necesaria para enfriar y calentar las edificaciones. Para estimar la cantidad de carbono almacenado por los tipos más pequeños de árboles urbanos, excluyendo las hojas y las raíces, se tomaron mediciones estándar para determinar la densidad y el volumen de madera, lo mismo que el peso seco de muestras seleccionadas de cultivares de *Amelanchier*, *Malus*, *Pyrus calleryana* y *Syringa reticulata*. La densidad de la madera se definió como el rango en peso específico de 0.53 a 0.64 g/cm^3 para todos los géneros. Las densidades en las dos porciones superiores del tronco fueron significativamente diferentes a las de la base. La densidad de la madera de *Syringa reticulata* fue significativamente menor que la de los otros géneros. Los análisis de regresión del peso de la madera, basado en la altura y diámetro de los árboles arriba de 12 cm de dap, indicaron una relación lineal en *Amelanchier*, pero las ecuaciones curvilíneas (no lineales) explicaron mejor la variación en *Malus* y *Pyrus*. Los árboles más pequeños, aquellos con 2.3 a 4.9 cm de dap, almacenaron típicamente entre 2.1 a 2.3 Kg. de carbono en troncos y ramas; los árboles entre 5.0 y 7.9 cm almacenaron entre 8.4 a 15.1 Kg., y los árboles más grandes, de 8.0 a más de 11.7 cm, almacenaron entre 24.5 a 37.5 Kg. de carbono. El árbol de copa estrecha *Pyrus calleryana* 'Capital' almacenó considerablemente menor cantidad de carbono que los otros cultivares. Estas estimaciones pueden incrementarse en un 22% si se añade el carbono almacenado en las raíces, de acuerdo con otros estudios.