QUANTIFYING THE ROLE OF URBAN FORESTS IN REMOVING ATMOSPHERIC CARBON DIOXIDE

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Abstract. Urban land in the United States currently occupies about 69 million acres with an estimated average crown cover of 28% and an estimated tree biomass of about 27 tons/acre. This structure suggests that the current total urban forest carbon storage in the United States is approximately 800 million tons with an estimated annual net carbon storage of around 6.5 million tons. Besides directly storing carbon, urban trees also reduce carbon dioxide (CO2) emissions by cooling ambient air and allowing residents to minimize annual heating and cooling. Approaches for understanding urban trees and CO2 flux are described at four scales: the nation, the city, the organization, and the individual. A method is provided that allows one to easily estimate the amount of carbon stored in an urban forest and sequestered annually by that forest. A method is provided for organizations to calculate the number of trees necessary to offset the CO2 emissions associated with the energy used in their office buildings. Tables are also provided to show how many trees an American could steward or plant to offset his or her per capita carbon emissions (2.3 tons/year).

In the past few years, with increasing amounts of atmospheric carbon dioxide (CO_2) there has been a growing interest in understanding how much carbon urban forests store and sequester. This paper addresses this concen at multiple scales. It: 1) estimates the total carbon stored and annually sequestered by urban forests in the United States, 2) provides a methodology to enable urban foresters to estimate their own urban forest's carbon storage and sequestration, and 3) estimates the number of trees necessary to compensate for carbon production at the organizational and individual level.

Carbon Storage and Sequestering by Urban Forests in the United States.

Average Urban Crown Cover. Crown, or canopy, cover ranges within any city from next to nothing in dense commercial areas to as high as 100% in some parks and natural areas. Based on tree canopy cover data from 26 cities in the United States, we have derived a preliminary estimate of average urban canopy cover in the United States as 28%. This estimate is currently being refined as more data become available.

Urban Tree Biomass and Carbon. To estimate the relationship between crown cover and stored carbon, we first estimated the average number of trees/acre for an area with 28% tree cover. This tree density estimate was derived using: 1) an average diameter distribution derived from a summary of street tree diameter distributions given in McPherson and Rowntree (6), 2) formulae of hardwood crown spread from diameter (2) which was converted to crown area, and 3) a ratio of hardwood to conifer crown spread derived from Winer et al. (14). We assumed a forest composition of 75% hardwoods and 25% conifers.

Based on the estimated number of trees/acre and diameter distribution, total fresh-weight biomass/acre (above and below ground biomass) was calculated using equations given in Wenger (12). These biomass equations were intended for use on trees up to 26 inches in diameter but were extended to 35 inches. A sugar maple (Acer saccharum) formula was used to represent hardwood biomass and a white pine (*Pinus strobus*) formula for conifer biomass. Hardwood dry weight was estimated to be 60% of fresh weight; conifer dry weight 46% (10,11,15). Carbon storage is approximately 45% of total dry weight biomass (4,13).

From these formulae, an urban forest with 28% cover would have, on average, about 21 trees/acre, 27 tons of dry weight biomass/acre, and a total of 12 tons of stored carbon per acre. Given that the urban land in the United States is thought to occupy approximately 69 million acres (3), the total number of urban trees in the United States is estimated at 1.5 billion (approximately six trees to every American) with a total of 800 million tons of

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stored carbon. These estimates include all trees within urban lands, including vacant parcels, residences, street trees, and so on.

Annual Sequestering of CO_2 by Urban Forests. To estimate annual urban forest carbon sequestration, it was necessary to estimate annual growth, mortality, and leaf loss. Carbon sequestered by trees during growth minus carbon released due to tree mortality and leaf loss will yield the net urban forest change in carbon.

Equations for urban tree growth were derived from age/dbh relations given in Fleming (2). For diameter classes between 6 and 32 inches, annual growth was considered to be 0.57 inches. For trees less than 6 inches, annual growth was considered to be 0.32 (6/19) inches (a 6-inch tree was 19 years old). For trees larger than 32 inches (64 years old), annual growth rate was assumed to taper off from 0.57 to 0.32 inches/year at year 100 in increments of 0.007 inches/year. Biomass equations were used to calculate the amount of biomass accrued given these growth rates and the appropriate diameter distribution.

Estimates of annual mortality rates by diameter class were derived from a study of street tree mortality in Syracuse, New York (7). Urban forest leaf biomass was estimated by converting average crown area for hardwoods and conifers within diameter classes to average leaf biomass (dry weight) by a conversion formula derived from Winer et al. (14). To calculate leaf drop, it was assumed that 90% of hardwood leaves and 25% of conifer leaves (3-year needle retention) would be dropped. The amount of carbon lost due to mortality and leaf drop was subtracted from the amount sequestered due to growth to yield the net sequestration rate. Using this methodology, the net amount of carbon sequestered by urban forests in the United States is estimated at about 6.5 million tons/year.

Is this a lot?

Conservative Estimates. The estimates of numbers of urban trees, carbon storage, and net sequestration are conservative because: 1) crown width estimates were derived from a street tree population, and most urban trees will likely have smaller crown widths, thus increasing the number of urban trees above the estimate we used, 2) understory trees were not included, 3) replanting efforts were not considered, and 4) carbon storage by other types of vegetation (e.g., shrubs, grass) and soils were not considered.

Using street tree mortality estimates (7), we estimate that approximately 39 million urban trees die annually. If these trees were replanted or seeded in naturally with 1-inch caliper trees, approximately 64,000 more tons of carbon would be sequestered in the first year.

Estimating Carbon Storage and Sequestration of Individual Urban Forests. To estimate carbon stored and sequestered by trees in a particular city or portion of a city, it is necessary to have an estimate of the number of acres in the area and the percentage of crown cover. In addition, an estimate of the diameter distribution of the population will lead to a better estimate of carbon storage and sequestration.

McPherson and Rowntree (6) found three predominant diameter distributions of street tree populations across the United States. A Type 1 distribution characterizes a young population and was found in 36% of the cities analyzed. A Type 2 distribution represents a population with a moderate amount of plantings 10-20 years ago and was associated with 32% of the cities analyzed. A Type 3 distribution has a nearly even amount of trees in all diameter classes and was also encountered in 32% of the cities analyzed. These three types of diameter distributions were weighted by the proportion of cities in which they occurred to obtain the "average" diameter distribution (Table 1).

To estimate total tons of carbon stored per acre (Figure 1), multiply percent cover (0-100) by 0.3226 for Type 1 distribution, 0.4423 for Type 2, 0.5393 for Type 3, and 0.4303 for the Average distribution. If the diameter distribution is unknown, the Average distribution is the best to use. To estimate the annual amount of carbon sequestered per acre in an area (Figure 2), multiply percent cover by 0.00727 for a Type 1 distribution, 0.00077 for Type 2, 0.00153 for Type 3, and 0.00335 for the Average distribution. To obtain the total amount of carbon stored or annually sequestered in an area, multiply the carbon/acre estimate by the number of acres in the area.

For example, the city of Syracuse, New York,

Table 1. Percent of population within 6-inch diameter classes with Type 1-3 population distributions (6) and average of all three distributions.

Distrbution type	*0-6*	*7-12*	*13-18*	*19-24*	*25-30*	*<30*
	Diameter class (in.)					
Type 1	42	27	14	10	6	1
Type 2	21	29	26	8	8	8
Type 3	23	15	20	16	18	8
Avg.	29	24	20	11	11	6

occupies 10,980 acres with 24% tree cover (8). Syracuse's total carbon storage is estimated at 115,000 tons of carbon (10,980 X 24 X 0.4303), using the Average diameter distribution, with an annual carbon sequestration rate of 880 tons (10,980 X 24 X 0.00335). The average annual mortality rate for urban forests (Average diameter distribution) is 0.57 trees/acre. Thus, for Syracuse to maintain its current stocking and storage level, an estimated 6,250 trees need to be planted or naturally seeded in annually (10,980 X 0.57).

Urban Forests in the Future. The average annual sequestration rates are highly sensitive to the growth and mortality assumptions. Areas with higher mortality and/or lower growth rates than used in our assumptions may lose more carbon to the atmosphere than they sequester. An important factor about the annual sequestration rates is the relative difference in sequestration based on diameter distribution. The Type 1 distribution, a young population, by far sequesters the most carbon annually. This relatively large carbon sequestering ability by a young population suggests that tree planting in urban areas can have an impact on atmospheric CO_2. Future studies, though, need to subtract the amount of CO_2 emitted from vehicles and machines used in tree planting and maintenance, from the amount of CO_2 sequestered by trees. This comparison will emphasize the importance of minimizing young-tree mortality to avoid a net CO_2 addition to atmosphere from the tree planting process.

The present urban forest in the United States stores approximately 800 million tons of carbon. This amount leads to a strong argument for at least maintaining present urban forest stocking. Decreases in current stocking due to tree mortality will release large amounts of carbon. Future tree

good point: when a tree dies, it decomposes its CO2 back to the atmosphere

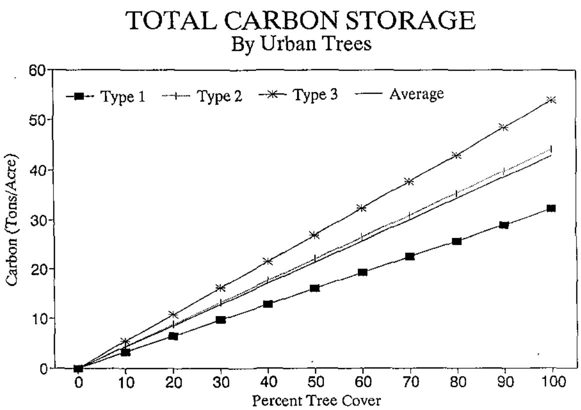

Figure 1. Estimates of tons of carbon stored per acre for urban forests of varying tree cover. Estimates are given for 4 different diameter distributions (Type 1-3 and Average - see Table 1).

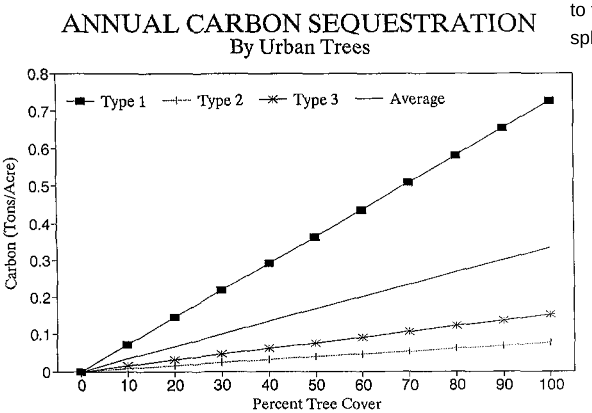

Figure 2. Estimates of tons of carbon sequestered annually per acre for urban forests of varying tree cover. Estimates are given for 4 different diameter distributions (Type 1-3 and Average - see Table 1).

planting to maintain or increase stocking levels can increase the carbon sequestering rate of the urban forest. An estimated 39 million urban trees die annually. Some of these trees are replaced through natural regeneration, but to maintain current stocking, the remainder must be planted.

If the United States could increase average urban tree cover by 5% (from 28% to 33%) over the next 50 years, the urban forests could store an additional 150 million tons of carbon. To increase cover by five percent, 250 million more trees would need to be established over the next 50 years (5 million a year), in addition to the annual replanting of 39 million trees lost to mortality (a total annual replanting or natural reseeding of 44 million trees). This replanting estimate assumes that all of the planted trees will survive. This estimate must be adjusted upward in proportion to the mortality rate for newly planted trees.

Helping Organizations Offset Their Carbon Dioxide Emissions

Many organizations want to offset the amount of CO_2 emitted by the utilities which supply their buildings with energy. Calculations for one such organization wanting to plant seedlings to offset their CO_2, serves as an example (9).

The building is occupied by the Dutchess County Environmental Management Council (Millbrook, New York) and utilized 160,740 kilowatt-hours (kwh) of electricity and 9,021 gallons of No. 2 fuel oil for its operation in 1989 (Gersh, pers. comm., Dutchess Co. Envir. Mngt. Council, 1990). To determine the "carbon cost" of operating this building, we first calculated the fuels used to generate the electricity. Eighty-nine percent of the electricity was generated at two power plants, one burning oil, the other assumed to burn an equal mix of oil, coal, and natural gas. Each plant was assumed to provide an equal amount of electricity to the building. The remaining 11% was generated at nuclear or hydroelectric plants (Gersh, pers. comm., 1990). We assumed there was negligible CO_2 produced from the nuclear and hydroelectric plants.

The amount of CO_2 produced per Quad (10^{15} Btu or 293 x 10^9 kwh) of electrical generation at power plants was 20.2 million tons for oil-based power plants; 27.8 million tons for coal based; and 15.9 million tons for natural gas power plants (Garbesi, pers. comm., Lawrence Berkeley Laboratory, 1989). The total amount of carbon dioxide produced in generating the electricity used by the building in 1989 was 10.1 tons.

Carbon dioxide was converted to the amount of carbon using atomic weights. With atomic weights, one ton of CO_2 contains 0.273 tons of carbon. Thus, the building was responsible for 2.8 tons (10.1 x 0.273) of carbon emission due to electrical use.

During 1989, the building required 9,021 gallons of No. 2 heating oil. Given that liquid fuel derived from crude oil produces approximately 2.25 x 10^{-8} tons of carbon/Btu (5), and there are 138,600 Btu/gallon of No. 2 fuel oil (Gersh, pers. comm., 1990), the building's fuel oil consumption produced 28.1 tons of carbon in 1989. Thus, the total carbon produced by operating this building in 1989 was 30.9 tons. It is important to note how much more carbon was emitted for heating the building (28.1 tons) than for the electricity to light and air condition the building, and to run the office machines (2.8 tons). Because trees can be used to reduce heating costs, the potential magnitude of their effect is large.

Determining the Number of Trees Necessary to Offset Building Carbon Production. Figure 3 shows the estimated annual carbon budget of one hardwood tree (sugar maple) and one conifer tree (white pine) over the first 100 years of growth based on methods provided earlier. By summing these sequestering rates over time, the number of years necessary for the planting of 500 and 1,000 hardwoods (Figure 4) and conifers (Figure 5) to sequester the carbon produced by the operation of the building can be calculated. The approximate diameters for the ages (years) listed in Figures 3-5 are given in Table 3. A note of caution: biomass equations were extended beyond their intended diameter ranges and data beyond year 60 become increasingly uncertain.

The white pine and sugar maple seedlings/saplings were assumed to be 1/8 inch in stem diameter (dbh) at the time of planting. To estimate leaf drop, we assumed 25% of the conifer needles (3-year needle retention) and 100% of the hardwood leaves would be dropped each year.

The equilibrium points at which the amount of carbon stored in the trees equals the cumulative amount of carbon produced by the building is estimated at greater than 100 years for both 500 hardwood and 500 conifer trees; and 60 years for both 1,000 hardwood and 1,000 conifer trees (Figures 4 and 5). No difference in equilibrium points was found between the hardwood and conifer trees as their annual net sequestration rates are very similar (Figure 3). Past these equilibrium points, the trees store more carbon than the building has produced since the seedlings were planted. These calculations assume no tree mortality. A longer growth period or more trees will need to be planted if some of the planted trees die.

Trees to Reduce Building Energy Consumption. Through properly locating trees to act as winter windbreaks, provide summer shade and allow winter solar access, trees can reduce a building's heating and cooling requirements (and carbon production) by 15% (Heisler, pers. comm., Northeastern Forest Exp. Sta., 1990). By reducing the carbon production of buildings, the time necessary to reach the equilibrium points is shortened by about 15 years for 500 conifer trees, ten years for 500 hardwood trees and five years for 1,000 hardwood or conifer trees.

Helping Individuals Offset Their Per Capita Carbon Emissions

The per capita carbon emission rate in the United States is 2.3 tons/year (1). Because of urbanization, industrialization, and the use of automobiles, the United States tops the world's per capita ranking. Per capita carbonemission rates (in tons) for other countries are: Canada = 1.8; USSR = 1.6; Western Europe = 0.9; Japan = 0.9; China = 0.2; and India = 0.1.

We have designed and circulated approximately 5000 brochures ("How Many Trees Does It Take to Store the Carbon You Produce") that present this information and encourages individuals to take responsibility for planting or stewarding enough trees to account for his or her portion of America's carbon emissions. This approach has had a positive response. The brochure stresses stewardship for the person's lifetime to counter

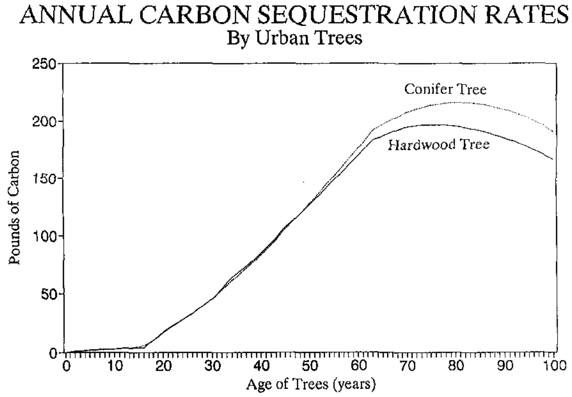

Figure 3. Annual carbon sequestration rates for one hardwood tree (sugar maple, *Acer saccharum*) and one conifer tree (eastern white pine, *Pinus strobus*).

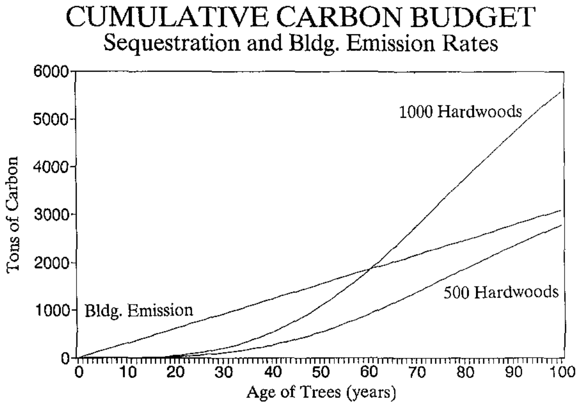

Figure 4. Cumulative amount of carbon sequestered by 500 and 1,000 hardwood trees (sugar maple, *Acer saccharum*), and emitted by a building with an annual carbon emission rate of 30.9 tons.

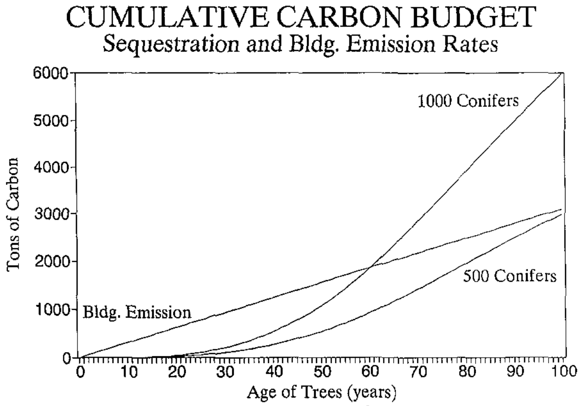

Figure 5. Cumulative amount of carbon sequestered by 500 and 1,000 conifer trees (eastern white pine, *Pinus strobus*), and emitted by a building with an annual carbon emission rate of 30.9 tons.

the misconception that one can do their part by just planting a seedling and not following up with tree care. For example, to remove and store the per capita carbon produced during the remainder of their lives, 20-year old individuals need to plant and care for 80 seedlings. A 50-year old needs to plant and care for 550 seedlings. The sooner one gets started, the fewer trees are required. A newborn baby needs only 45 seedlings to sequester all the carbon for his or her lifetime. The assumptions are that the seedlings will survive the remainder of the participant's life and the per capita carbon emissions remains constant. There are other options besides planting trees. One can choose to steward established trees. Table 2 is a guide for how many seedlings, or 15 gallon (1" dbh) saplings, or 10-year-old (approximately 3" dbh) trees need to be planted or stewarded.

For stewarding trees older than 10 years, one can employ a rule of thumb that suggests only half as many trees in the 10-year-old column (Table 2) need to be stewarded if they are twice that diameter, or about 6 inches dbh. Stewarding large trees prevents their relatively large store of carbon from being released while allowing other benefits to be sustained (e.g., shade, wildlife habitat, etc.). The death and decay of one 70-year-old tree will release about 3 tons of carbon. Finally, with only about six urban trees for each American, there are not enough existing trees for every American to assume stewardship. Thus, tree planting is a necessity.

Final Comment

These estimates of urban forest carbon storage and sequestration are derived from limited empirical data, but do reveal the magnitude of the effect urban trees have, and can have, on atmospheric carbon dioxide. Trees are only one way to reduce atmospheric carbon dioxide and will have an impact only as long as their structure is maintained. Planting trees now and allowing them to die in the future without replanting will produce only a short-term gain.

Urban foresters and citizens can help the urban forest sequester carbon by maintaining existing trees and by planting and maintaining trees in the future. Planting efforts must focus on putting the right tree in the right location and reducing early tree mortality.

Future studies quantifying urban forest structure, growth and mortality are needed to obtain better estimates of carbon sequestration by urban trees. These studies also need to quantify the total carbon budget of tree planting, maintenance, and removal, which includes CO_2 flux to the atmosphere from equipment and vehicles.

Table 2. The number of seedlings, 15 gallon (1" dbh) or 10 year old (3" dbh) trees required for an individual of a given age to steward for life to account for the 2.3 tons/year of per capita United States carbon dioxide emissions.

Age	*Number of seedlings*	*15 Gallon trees*	*10-Year-old trees*
0	45	40	30
10	60	50	35
20	80	65	40
30	120	85	50
40	210	135	70
50	550	255	95

Table 3. Approximate age-diameter relations (2) for Figures 3-5.

Age	*Diameter (in.)*
10	3
30	12
50	24
70	35
90	44

Acknowledgments. The authors thank B. Hudson, E.G. McPherson and R. Birdsey for critical reviews of this paper. We also express our gratitude to J. Stevens and J. Gersh for assisting with the acquisition of data.

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Résumé. Le domaine urbain aux États-Unis occupe habituellement environ 69 millions d'acres avec une moyenne de couverture de cimes estimée à 28% et une biomasse en arbres estimée à environ 27 tonnes à l'acre. Cette structure suggère que le total courant de carbone emmagasiné dans la forêt urbaine des États-Unis est, approximativement, de 800 millions de tonnes avec un emmagasinage annuel net de carbone estimé autour de 6.5 millions de tonnes. En outre du carbone directement emmagasiné, les arbres urbains réduisent aussi les émissions de gaz carbonique (CO_2) en refroidissant l'air ambiant et en permettant aux résidents de diminuer le chauffage et la climatisation annuels. Les approches pour la compréhension des arbres urbains et du flux de CO_2 sont décrites à quatre échelles: le pays, la ville, l'organisme et l'individu. Une méthode est fournie qui permet à un individu d'estimer aisément la somme de carbone emmagasiné dans une forêt urbaine et isolée annuellement par cette forêt. Une méthode est fournie aux organismes afin de calculer le nombre d'arbres nécessaire pour compenser les émissions de CO_2 associées à l'énergie utilisée dans les édifices à bureaux. Des tables sont aussi fournies pour indiquer combien d'arbres un Americain pourrait régir ou planter pour compenser ses émissions par individu en CO_2 (2.3 tonnes/année).

Zusammenfassung: Städtische Landbesitz nimmt zur Zeit in den USA ungefähr 28.29 Millionen Hektar ein, mit einer geschätzten Kronenbedeckung von 28% und einer geschätzten Baumbiomasse von ungefähr 11.07 Tonnen/Hektar. Diese Skizze deutet an, dass die heutige, gesamte Waldkohlenstoffspeicherung in den USA ungefähr 800 Millionen Tonnen ist, mit einem geschätzten einjährigen Nettokohlenstoffspeicherung von ungefähr 6.5 Millionen Tonnen. Städtische Bäume sind nicht nur da, um Kohlenstoff direkt zu speichern, sondern auch um durch das Abkühlen von der Umgebungstemperatur die Kohlendioxid-Emissionen zu reduzieren und infolgedessen das einjähriges Heizen und Kühlen auf ein Minimum zu bringen. Ann herungsversuche für das Verstehen städtischer Bäume und Kohlendioxidwechsel werden auf vier Ebenen beschrieben: Nation, Stadt, Organization und Individuum. Eine Methode wird dargestellt um einen ganz einfach, den im städtischen Wald gespeicherten Kohlenbetrag, der jährlich vom Wald gebraucht wird, zu schätzen. Eine Methode wird Organizationen dargeboten, um die Baummenge zu kalkulieren, die Kohlendioxid-Emissionen von der Bürohausenergieverwendung ausgleicht. Tabellen werden auch dargeboten um zu zeigen, wie viele Bäume jeder Amerikaner verwalten oder pflanzen könnte um seine eigene Kohlendioxid-Emissionen auszugleichen (2.3 Tonne/Jahr).