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Atmospheric Carbon Reduction by Urban Trees

David J. Nowak

USDA Forest Service, Northeastern Forest Experiment Station, 5801 N. Pulaski Rd, Bldg C., Chicago, Illinois 60646, U.S.A.

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Trees, because they sequester atmospheric carbon through their growth process and conserve energy in urban areas, have been suggested as one means to combat increasing levels of atmospheric carbon. Analysis of the urban forest in Oakland, California (21% tree cover), reveals a tree carbon storage level of 11·0 metric tons/hectare. Trees in the area of the 1991 fire in Oakland stored approximately 14 500 metric tons of carbon, 10% of the total amount stored by Oakland's urban forest. National urban forest carbon storage in the United States (28% tree cover) is estimated at between 350 and 750 million metric tons. Establishment of 10 million urban trees annually over the next 10 years is estimated to sequester and offset the production of 363 million metric tons of carbon over the next 50 years—less than 1% of the estimated carbon emissions in the United States over the same time period. Advantages and limitations of managing urban trees to reduce atmospheric carbon are discussed.

Keywords: urban forestry, carbon storage, greenhouse effect, urban wildfire.

1. Introduction

Increasing levels of atmospheric carbon dioxide (CO_2) and other "greenhouse" gases are thought by many to be leading to increased atmospheric temperatures through the trapping of certain wavelengths of heat in the atmosphere. This increase in atmospheric CO_2, the predominant greenhouse gas, is largely attributable to fossil fuel combustion and deforestation. Atmospheric carbon is estimated to be increasing by approximately 2·6 billion metric tons (t) annually (Sedjo, 1989). Trees, through their growth process, act as a sink for atmospheric carbon. Thus, increasing the amount of trees can potentially slow the accumulation of atmospheric carbon. Managers in urban areas must be aware of the potential of trees to mitigate atmospheric carbon, one of many benefits derived from urban trees.

In terms of atmospheric carbon reduction, trees in urban areas offer the double benefit of direct carbon storage and the avoidance of carbon production by fossil-fuel power plants through energy conservation from properly located trees. Limited work has been done that analyzes the amount of carbon urban forests do and can store, and the effect of energy conservation on the amount of carbon released to the atmosphere.

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Biomass of trees in Shorewood, Wisconsin, a suburb of Milwaukee, has been estimated at 32·5 t of above-ground biomass per hectare (Dorney *et al.*, 1984). Biomass was calculated using only one biomass formula from Whittaker *et al.* (1974) to represent all species. This biomass estimate converts to approximately 18·3 t of carbon (above and below ground) per hectare. Shorewood's tree cover has been liberally estimated at 39%, with approximately 67% of the trees less than 15 cm in diameter (dbh) (Dorney *et al.*, 1984).

Rowntree and Nowak (1991) have modeled urban forest carbon storage and sequestration. This model uses biomass formulas for sugar maple (*Acer saccharum*) and eastern white pine (*Pinus strobus*) to represent hardwood and conifer biomass, respectively. These biomass equations are incorporated with other pertinent information derived from the literature (e.g. diameter distributions, growth and mortality rates, leaf loss, etc.) to estimate carbon storage and annual sequestration rates.

With an estimated average tree cover of 28% in U.S. urban areas, Rowntree and Nowak (1991) estimate that U.S. urban forests average approximately 60 t of biomass/ha and 27 t of stored carbon/ha. These estimates are based on a diameter distribution with 29% of trees less than 15 cm dbh; 24%—16–30 cm; 20%—31–46 cm; 11%—47–61 and 62–76 cm; and 6% greater than 76 cm. Approximately 725 million t of carbon (above and below ground) are estimated to be stored within urban trees in the United States using this diameter distribution (Rowntree and Nowak, 1991).

In addition to the benefits received by carbon storage and avoidance of urban trees, urban trees can also fuel wildfires and release large amounts of carbon during urban wildfires. On 20–21 October 1991, a wildfire in the Oakland hills burned across approximately 625 ha of land, destroying 3210 homes and apartments, killing 26 people and creating over 1·5 billion dollars in damage (Oakland Office of Emergency Service, 1991). Although research is currently being designed to look at the effect urban trees had on the spread of this recent fire, and what effect the fire had on the trees, this paper will report on the potential carbon released from urban trees due to the fire.

In addition, this paper will estimate total tree carbon storage in Oakland, California, extrapolate this estimate to national urban tree carbon storage, and compare this result with Rowntree and Nowak's (1991) modeling estimate. This paper will also explore the effect of future tree plantings in urban areas on levels of atmospheric carbon.

2. Methods

Tree cover was estimated using random dot grid sampling (5·6 dots/cm^2) of 1988, 1:12 000 black and white aerial photographs. Each dot was classified with regards to census tract area, cover type and land use type.

2.1. GROUND SAMPLING

Ground sampling of the urban forest in Oakland was conducted in 1989. The city was divided into three separate strata for ground sampling. The first stratum, which consisted of residential, commercial, industrial and small transportational lots, used block fronts (i.e. all land along one side of a block: front and back yards) as the sampling unit.

Block fronts were randomly selected within each land use type until 5% of the total block front distance was selected. All street and front-yard trees on selected block fronts were recorded. Only back-yard trees with their vertical axis (main stem) visible from around the sides of structures were recorded from the front lots. This type of "side-view" sampling was done to avoid underestimating small tree species. To account for missing trees due to this "side-view" sampling, the number of back-yard trees on each sampled block was measured from aerial photographs in conjunction with a calculated proportion of understory trees that could not be viewed from aerial photos. Five per cent of other land use block fronts were also randomly sampled to obtain a more accurate representation of street trees.

The second stratum consisted of smaller institutional land uses (e.g. schools, hospitals, churches, intensively managed parks) and was analyzed using a 5% sample of variable parcel sizes based on individual land parcels of known size.

The final stratum consisted of wildland, large transportational, large institutional and miscellaneous land uses and was analyzed using a 5% sample of 0·1-ha plots. All trees on each plot/parcel were measured.

In all strata, species, diameter (dbh) and height, along with other information, were noted for each tree sampled. Total area or block front distance was known for each stratum and land use.

2.2. CARBON AND TREE BIOMASS

Biomass for each tree sampled was calculated using allometric equations derived from the literature (Table 1). If no allometric equation could be found for an individual species, then the genera average was substituted, or if no genera equations were found, the biomass was computed separately for each hardwood and conifer equation and the results were averaged for hardwood and conifer groups. Palms were omitted from biomass calculations due to lack of biomass formulas and their relatively insignificant contribution to total biomass.

Biomass equations for urban trees have not been estimated, and forest-grown tree equations were used. Biomass equations vary as to what portion of tree biomass they calculate, whether they estimate fresh or oven-dry weight, and the diameter ranges used to devise the equations (Table 1). Tree biomass is distributed with approximately 20% of the biomass in the crown, 60% in merchantable stem to 10-cm top and 20% in the stump/root system (Husch *et al.*, 1982; Wenger, 1984). Equations that compute above-ground biomass were divided by 0·8 to convert to total tree biomass. Equations that compute merchantable biomass were divided by 0·6.

Equations that compute fresh-weight biomass were multiplied by 0·46 for conifer trees and 0·56 for hardwood trees to yield dry weight biomass. These conversion factors were derived from average species moisture contents given in the literature (USDA Forest Service, 1955; Young and Carpenter, 1967; Wartluft, 1977; Stanek and State, 1978; Wartluft, 1978; Ker, 1980; Phillips, 1981; Husch *et al.*, 1982).

For dead and dying trees, leaf biomass was removed from the total tree biomass estimate by reducing the biomass estimate by 3·7% for conifers and 2·5% for hardwoods. These leaf biomass conversions were calculated using biomass equations that calculate both leaf and total biomass for the same species (Ker, 1980; Tritton and Hornbeck, 1982; Jokela *et al.*, 1986). The average diameter of dead and dying trees (18 cm) was used in the biomass equations to calculate per cent leaf biomass.

Total tree dry-weight biomass was converted to total stored carbon by multiplying by 0·45 (Lieth, 1963; Whittaker and Likens, 1973).

Ratio estimates (Cochran, 1977) of carbon storage per block front or unit area were used to calculate the total carbon stored within land use types.

TABLE 1. Attributes of biomass equations used to calculate tree biomass in Oakland

Species	Tree part	Tree weight	Dbh range (cm)	Reference
American arborvitae	Above	Dry	3–30	Ker (1980)
American beech	Above	Dry	5–51	Tritton and Hornbeck (1982)
Aspen	Total	Fresh	3–51	Wenger (1984)
Balsam fir	Total	Dry	3–41	Stanek and State (1978)
Black cherry	Above	Dry	5–51	Tritton and Hornbeck (1982)
Black oak	Total	Dry	28–86	Stanek and State (1978)
Blue gum	Above	Dry	5–25	Negi and Sharma (1987)
Coast live oak	Merch	Fresh	5–140	Pillsbury and Stevens (1978)
Cork oak	Above	Dry	5–36	Canadell *et al.* (1988)
Douglas fir	Total	Dry	3–122	Wenger (1984)
Eastern hemlock	Total	Dry	15–38	Stanek and State (1978)
Eastern white pine	Total	Fresh	3–66	Wenger (1984)
Eucalyptus hybrid	Above	Dry	5–30	Negi and Sharma (1987)
Green ash	Abv-lf	Dry	3–79	Schlaegel (1984*a*)
Hickory	Total	Fresh	5–69	Wenger (1984)
Jack pine	Above	Dry	3–33	Stanek and State (1978)
Lodgepole pine	Total	Dry	10–33	Stanek and State (1978)
Longleaf pine	Total	Fresh	15–48	Wenger (1984)
Norway spruce	Above	Dry	13–41	Jokela *et al.* (1986)
Paper birch	Total	Dry	15–28	Stanek and State (1978)
Pin cherry	Above	Dry	3–23	Tritton and Hornbeck (1982)
Red and white spruce	Total	Fresh	3–66	Wenger (1984)
Red alder	Above	Dry	3–152	Stanek and State (1978)
Red maple	Total	Dry	15–28	Stanek and State (1978)
Red oak	Above	Dry	5–51	Tritton and Hornbeck (1982)
Red pine	Total	Fresh	3–51	Wenger (1984)
Scarlet oak	Abv-lf	Dry	15–51	Clark *et al.* (1980)
Shortleaf pine	Total	Fresh	15–51	Wenger (1984)
Slash pine	Total	Fresh	15–53	Wenger (1984)
Sugar maple	Total	Fresh	3–66	Wenger (1984)
Sweetgum	Abv-lf	Dry	3–84	Schlaegel (1984*b*)
Tulip poplar	Above	Dry	5–51	Tritton and Hornbeck (1982)
Western red cedar	Above	Dry	3–119	Stanek and State (1978)
White ash	Above	Dry	5–51	Tritton and Hornbeck (1982)
White oak	Above	Dry	5–51	Tritton and Hornbeck (1982)
Yellow birch	Total	Fresh	3–66	Wenger (1984)

Above, above-ground biomass.
Abv-lf, above-ground biomass excluding leaves.
Merch, merchantable stem to 10-cm top.
Total, total tree biomass (including roots).
Weight, fresh or oven dry weight.

2.3. NATIONAL URBAN FOREST CARBON STORAGE

In a study of four eastern cities, Rowntree (1984) concluded the relative amount of land occupied by various land uses does not vary much among cities, with an average 50% of the city occupied by residential lands; 16% institutional (including parks), 15% commercial/industrial, 13% vacant, 4% transportation and 3% other.

Per hectare estimates of carbon storage by land use (from Oakland) were applied to this land use distribution, extrapolated to an estimated 27 900 000 ha of urban land in the United States (Grey and Deneke, 1986) with a 28% national urban tree cover (Rowntree and Nowak, 1991), to produce an estimate of total stored carbon by urban trees in the United States.

To evaluate the model developed by Rowntree and Nowak (1991), Oakland's diameter distribution was input into the model to compare the model's revised estimate of national carbon storage versus the estimate derived from Oakland.

2.4. EFFECT OF 1991 FIRE ON TREE CARBON STORAGE IN OAKLAND

To determine the amount of carbon potentially released by the recent fire in Oakland, amount of land burned and tree cover (pre-fire) within land use types were estimated from aerial photos of the burn area and 1988 aerial photographs. Amount of carbon stored per hectare for each per cent of tree cover within land use types was extrapolated to the burn area based on the amount of tree cover in the burned land use areas.

2.5. FUTURE CARBON SEQUESTRATION AND AVOIDANCE

To calculate future carbon sequestration by urban trees, a scenario of the establishment of 10 000 000 urban trees (0·3 cm dbh) annually for the next 10 years was modeled using assumptions given in Rowntree and Nowak (1991). Seventy-five per cent of these trees are to be established around residences, the remainder around commercial buildings. This model assumes no mortality of the established trees and models cumulative carbon sequestration over the next 50 years.

In addition to direct sequestration of carbon, the amount of carbon production avoided from power plants due to building energy conservation from urban trees is included. Akbari *et al.* (1989) estimate that the establishment of 100 million mature urban trees around residences and commercial building would save 8·2 million t of carbon annually due to energy conservation.

3. Results

Oakland's urban forest is relatively small, with 61% of its trees less than 15 cm in diameter (dbh) (Figure 1). Most of Oakland's trees are in wildland areas with the fewest trees existing in commercial/industrial areas (Table 2). Its urban forest is dominated by blue gum (*Eucalyptus globulus*), Monterey pine (*Pinus radiata*), coast live oak (*Quercus agrifolia*) and California bay (*Umbellularia californica*) (Nowak, 1991). These four species comprise 50·7% of the total number of trees [standard error (SE) = 2·8%] and 49·1% of the total tree cover (SE = 2·1%).

This predominantly small-diameter urban forest structure currently stores 145 800 t of carbon (11·0 t of carbon/ha). The largest carbon storage is in wildland areas, the smallest in commercial/industrial areas (Table 3).

Extrapolating Oakland's carbon storage estimate to the national U.S. urban forest, the national urban forest is estimated to store 400 million t of carbon (14·3 t/ha).

Inputting Oakland's diameter distribution in the carbon model developed by Rowntree and Nowak (1991), the model estimates national urban forest carbon storage at 328 million t.

The amount of carbon stored by the trees in the October 1991 burn area of Oakland is estimated at 14 500 t.

Establishing 10 million urban trees annually over the next 10 years (1991–2000), and

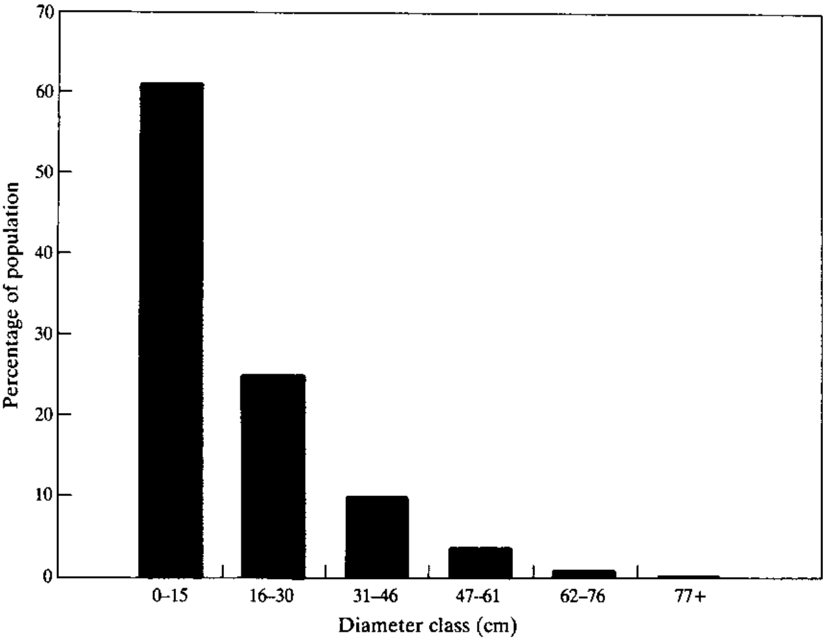

Figure 1. Diameter distribution of urban trees in Oakland, California (1989).

TABLE 2. Tree density (trees/ha), tree cover (%) and total number of trees for land uses within Oakland, California

Land use	Tree density		Tree cover		No. of hectares	Tree total	
	Mean	SE	Mean	SE		Total	SE
Wildland	292·3	15·3	45·9	0·5	2628	768 000	40 200
Institutional	111·9	10·3	18·3	0·6	1348	150 800	13 800
Residential	97·0	3·7	21·2	0·3	5791	561 500	21 200
Transportation	33·4	9·0	3·8	0·2	1932	64 500	17 400
Comm/indust	10·1	1·0	2·2	0·2	1542	15 600	1600
Entire city	119·9	3·8	21·0	0·2	13 241	1 587 700	50 600

SE, standard error.
Comm/indust, commercial/industrial.
Street trees = 27 300 (SE = 1400).
Miscellaneous land uses (36 ha, 0·7% tree cover) were categorized within institutional land use.

allowing them to survive over the next 50 years, will enable that tree population of 100 million trees to store 77 million t of carbon by the year 2040. In addition, these trees will avoid the production of another 286 million t of carbon, for a total of 363 million t of stored and avoided carbon over the next 50 years (Figure 2).

TABLE 3. Metric tons (t) of stored carbon per hectare (above and below ground by trees) and total metric tons of carbon stored for land uses within Oakland, California. To calculate total tree biomass (dry weight) divide figures by 0·45.

Land use	Carbon (t) per hectare		No. of hectares	Total stored carbon (t)	
	Mean	SE		Total	SE
Wildland	27·9	1·3	2628	73 400	3400
Institutional	12·9	1·5	1348	17 400	2000
Residential	8·8	0·5	5791	51 100	2900
Transportational	0·7	0·2	1932	1400	400
Commercial/industrial	0·5	0·1	1542	800	100
Entire city	11·0	0·4	13 241	145 800	4900

SE, standard error.
Carbon stored in street trees = 1700 t (SE = 150 t).
Miscellaneous land uses (36 ha) were categorized with institutional land use.

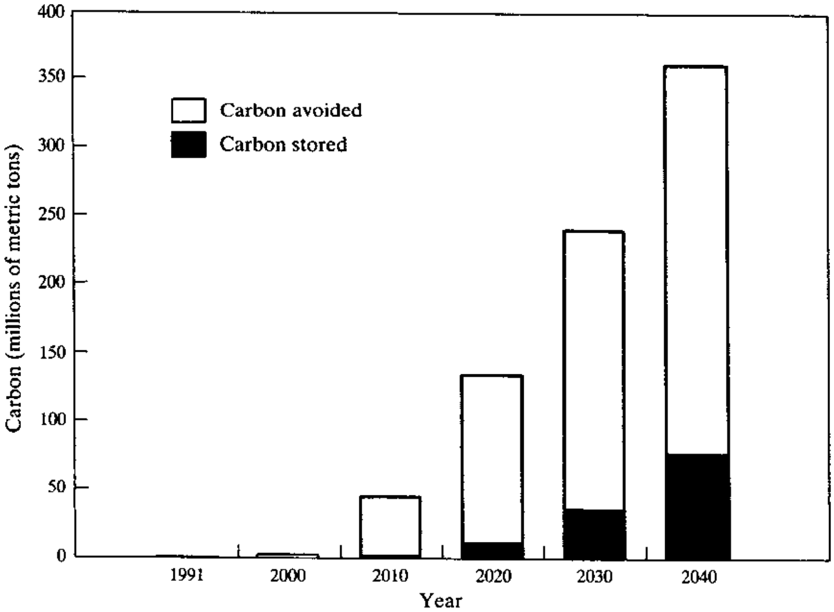

Figure 2. Cumulative amount of carbon stored and avoided by planting 10 million trees annually from year 1991 to year 2000. Amounts given assume no tree mortality.

4. Discussion

U.S. forest ecosystems store approximately 52·5 billion t of carbon, 31% in live trees, 59% in soils, 9% in litter, humus and woody debris, and 1% in live understory vegetation (Birdsey, 1990). These estimates convert to 55·0 t of carbon/ha in trees, 104·7 t of carbon/ha in soils, 16·0 t of carbon/ha in litter, humus and woody debris, and 1·8 t of carbon/ha in live understory vegetation.

Urban forest carbon storage estimates only include carbon stored by trees. Future research needs to evaluate carbon storage by other components of the urban forest ecosystem (e.g. soils, shrubs, grass).

Carbon storage levels given in this publication are based on the assumption that 45% of dry-weight biomass of trees is carbon (Lieth, 1963; Whittaker and Likens, 1973). Other research indicates that carbon is approximately 50% of dry-weight biomass (Koch, 1989). A 50% carbon to dry-weight biomass ratio would increase the carbon storage given in this report and the Rowntree and Nowak model by a factor of 1·1.

4.1. COMPARISON OF CARBON STORAGE ESTIMATES

Species and diameter distributions of urban trees are probably the most important parameters in determining stored tree carbon as tree species have different carbon storage rates and smaller trees have lower carbon storage levels than larger trees.

Two studies that have analyzed diameter distributions of trees from all land uses in a city indicate that the majority of trees have small diameters. In Shorewood, Wisconsin, approximately 67% of the trees are less than 15 cm in diameter (Dorney *et al.*, 1984); in Oakland, 61% are less than 15 cm in diameter (Nowak, 1991). The national urban forest carbon storage estimate (14·3 t/ha at 28% tree cover) is close to the tree carbon storage estimate derived for Shorewood, Wisconsin, (Dorney *et al.*, 1984) with its similar diameter distribution (13·2 t/ha at 28% tree cover). More studies of urban forests are needed to obtain a better estimate of structure (e.g. species composition, diameter distribution, tree cover) and how structure varies among cities.

Rowntree and Nowak's (1991) carbon model, which was admittedly conservative and based on a series of assumptions and limited allometric equations, appears to be a good, albeit conservative, estimate of urban tree carbon storage. Their model underestimated carbon storage by 18% based on Oakland's diameter distribution.

The conservative aspects of Rowntree and Nowak's 725 million t estimate of national U.S. urban forest carbon storage are probably offset by the liberal diameter distribution used in the model, with only 29% of the trees less than 15 cm dbh. Urban forests in the United States probably contain more small-diameter trees, so that a national urban tree carbon storage estimate of 350 to 750 million t appears more appropriate. More studies analyzing species composition, tree diameter distribution and carbon storage in cities are needed to test the sensitivity of the model estimates and refine estimates of national urban forest carbon storage.

4.2. MAINTAINING AND ENHANCING URBAN TREE CARBON STORAGE

The millions of metric tons of carbon currently stored by urban trees is a strong argument for at least maintaining the present urban forest structure. Loss of urban trees without replacement will act as a net carbon source to the atmosphere, both directly and indirectly (loss of energy conservation around buildings). Establishing more properly chosen and located urban trees, in addition to maintaining the present structure, can make urban forests a larger sink for atmospheric carbon, along with producing other urban forest benefits (e.g. temperature reduction, air pollution mitigation).

However, future tree plantings must survive to ensure they act as carbon sinks and not sources (i.e. trees must live long enough to compensate for the carbon produced due to planting and maintenance). Future research is needed to analyze the carbon budget of urban trees.

Trees are also only a short-term reservoir of carbon. Tree death and decay releases stored carbon back into the environment, so that future planting structures must be sustained to ensure these newly planted areas remain a long-term carbon sink. Although the benefit of carbon sequestering by trees will eventually be lost and the trees will need to be replanted, the additional benefit of carbon production avoided by urban trees, which can far outweigh the carbon directly sequestered, is avoided forever.

Although the absolute amount of carbon presently stored by urban trees in the United States is large, this amount is small relative to the magnitude of emissions. The U.S. national carbon storage estimate of 400 million t, which took years to store, is the amount of carbon (in the form of carbon dioxide) emitted in the United States in only about 4 months. The amount of carbon stored by Oakland's trees (145 800 t) is the amount of carbon (in the form of carbon dioxide) emitted in the United States in about 1 hour, or the amount emitted by Oakland residents' automobiles in approximately 8 months.

4.3. IMPACT OF 1991 FIRE IN OAKLAND

The impact of fire on releasing stored carbon goes well beyond the carbon directly released from the fire. The fire killed many trees, necessitating their removal and eventual decay (releasing stored carbon). In addition, many trees that survived in the burned area, as well as healthy trees outside of the burned area, will probably be removed in response to the fire in an attempt to reduce the potential of future fires.

Managers need to direct these post-fire tree removals, as well as pre-fire tree removals, by guiding forest structure in potential urban wildfire areas to a proper mix and distribution of species in order to reduce wildfire potential and spread while maintaining benefits derived from urban trees. The proper type, amount and location of vegetation to reduce the potential and spread of urban wildfires are specific to individual city environments and to the probability of occurrence of urban wildfires in the city. Research is currently being conducted to determine the effect of urban trees on the spread and intensity of wildfire.

In the 1991 burn area of Oakland, 14 500 t of carbon was stored by trees prior to the fire, 10% of the total amount of carbon stored by trees in Oakland. The actual amount of carbon that will be lost either directly or indirectly due to the fire remains to be determined, as the indirect anthropogenic response to the fire (healthy tree removals) will potentially occur for months or years to come.

4.4. FUTURE TREE PLANTINGS TO SEQUESTER AND AVOID CARBON EMISSIONS

Planting 100 million urban trees can store and avoid up to 363 million t of carbon over the next 50 years. This estimate compares with a potential annual carbon sequestration rate of 732 million t if 139 million hectares of non-urban land was planted with trees (Moulton and Richards, 1990).

Establishment of 100 million urban trees, when mature (crown area of 50 m^2), would increase national U.S. urban tree cover by 1·8%. These trees, being planted in residential and commercial areas, would increase tree cover on these land uses by approximately 3% each.

The urban estimate of 363 million t of carbon over the next 50 years is a liberal estimate, as all of the 100 million trees are expected to survive over the next 50 years. Even so, this estimate is still less than 1% of the amount of carbon estimated to be emitted in the United States over the same 50-year period. This 363 million t is also equivalent to increasing the present actual passenger automobile fuel efficiency from 8·7 km/l (Energy Information Administration, 1991) to 9·2 km/l over the next 50 years. This estimate assumes 2·08 trillion passenger automobile vehicle kilometres per year (Ross, 1989). At current 8·7 km/l (Energy Information Administration, 1991) and 0·6 kilograms of carbon in a litre of gasoline (Akbari *et al.*, 1989), fuel efficiency must increase 0·5 km/l over 50 years to equal 363 million metric tons of carbon.

5. Conclusion

More research is needed to get a better understanding of carbon cycling in urban forests. Research is needed that better quantifies growth and mortality rates of urban trees, tests the applicability of forest-derived allometric equations of tree biomass to urban tree situations, examines tree species and diameter distributions of urban forests throughout the United States, determines which tree species are the best for carbon sequestration and analyzes, through time, the carbon production (i.e. through planting and maintenance) and reduction (i.e. through sequestration and avoidance) by urban trees in an urban forest carbon budget.

Future planting of urban trees can have a small impact on the increasing levels of atmospheric carbon, but trees are only part of a solution. The principal ways to decrease carbon dioxide emissions, the predominant greenhouse gas, are increasing energy conservation and efficiency, and conversion to non-carbon or low-carbon fuels.

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