Available online at www.sciencedirect.com
SCIENCE DIRECT®
Urban Forestry & Urban Greening 3 (2005) 65–78
URBAN FORESTRY & URBAN GREENING
www.elsevier.de/ufug

The urban forest in Beijing and its role in air pollution reduction

Jun Yang[a,*], Joe McBride[a], Jinxing Zhou[b], Zhenyuan Sun[b]

[a]*Department of Environmental Science, Policy and Management, University of California at Berkeley, Berkeley, CA 94720-3110, USA*
[b]*Institute of Forestry Science, Chinese Academy of Forestry Science, Beijing 100091, China*

Abstract

Tree planting has been proposed by the municipal government as a measure to alleviate air pollution in Beijing, the capital of China. This study examines that proposal. It is based on the analyses of satellite images and field surveys to establish the characteristics of current urban forest in the central part of Beijing. The influence of the urban forest on air quality was studied using the Urban Forest Effects Model. The results show that there are 2.4 million trees in the central part of Beijing. The diameter distribution of the trees is skewed toward small diameters. The urban forest is dominated by a few species. The condition of trees in the central part of Beijing is not ideal; about 29% of trees were classified as being in poor condition. The trees in the central part of Beijing removed 1261.4 tons of pollutants from the air in 2002. The air pollutant that was most reduced was PM_{10} (particulate matters with an aerodynamic diameter smaller than 10 μm), the reduction amounted to 772 tons. The carbon dioxide (CO_2) stored in biomass form by the urban forest amounted to about 0.2 million tons. Future research directions to improve our understanding of the role of individual tree species in air pollution reduction are discussed.

Keywords: Urban forest structure; Ozone; Dry deposition; CO_2 sequestration

Introduction

Urban forests play an important role in improving the quality of the urban environment. A healthy, well-managed urban forest can provide many ecological benefits. For example, the urban forest can reduce storm water runoff (Xiao et al., 1998); alleviate the intensity of the heat island (Akbari and Konopacki, 2004), sequestrate CO_2 (McPherson, 1998a; Nowak, 1994b), and reduce air pollution (DeSanto et al., 1976; Dochinger, 1980; Nowak, 1994a; McPherson and Simpson, 1998). Among the benefits provided by urban forests, the function that is most important to Beijing, capital of China, is the ability of the urban forest to remove air pollutants from the atmosphere.

Like other metropolitan areas in developing countries, Beijing faces many environmental problems caused by poor urban planning and rapid development. Air pollution is the most outstanding of these. Beijing is among the ten cities of the world with the worst air pollution problem (World Bank, 2000). Severe air pollution causes serious health problems and loss of life. Research indicates that when the air pollution index (AQI) in Beijing rose by 10%, the daily number of deaths caused by respiratory disease increased by 3.52% (Zhang et al., 2003).

Trees can reduce air pollutants in two ways: (1) by direct reduction from the air, and (2) by indirect reduction by avoiding the emission of air pollutants.

*Corresponding author.
E-mail address: juny@nature.berkeley.edu (J. Yang).

1618-8667/$ - see front matter
doi:10.1016/j.ufug.2004.09.001

In direct reduction, trees absorb gaseous pollutants like sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and ozone (O_3) through leaf stomata and also can dissolve water-soluble pollutants onto moist leaf surfaces (Nowak, 1994a). Tree canopies can also intercept particulate matters in the air (Beckett et al., 1998). Indirectly, trees can reduce the air temperature through direct shading and evapotranspiration in the summer, thus reducing the emission of air pollutants from the process of generating energy for cooling purposes. Also, reduced air temperature can lower the activity of chemical reactions, which produce secondary air pollutants in urban areas (Taha, 1996; Nowak et al., 2000). Trees can also be a source of air pollutants; they emit biogenic volatile organic compound (BVOC). BVOC can react with nitro oxides (NO_x) and form O_3 and aerosols (Benjamin and Winer, 1998). The production of pollen by trees is a source of particles that can have serious health effects on people allergic to pollen (Beckett et al., 1998).

People have known that trees can help to reduce air pollutants for a long time. The Roman senate recognized the value of orchards in villas surrounding the city of Rome for maintaining air quality and forbid their conversion to urban housing (Cowell, 1978). In more recent times scientific studies have quantified the amount of air pollutants removed by trees in cities. DeSanto et al. (1976) studied the removal of five major air pollutants, SO_2, carbon monoxide (CO), O_3, NO_x and particulate matters by street trees in St. Louis area. Dochinger (1980) conducted early studies of the interception of particulates by trees. In these studies, the air-pollutants reduction effects of the urban forest were calculated by extrapolating the field measurements of several trees to the whole urban forest. There are, however, problems with this approach. Primary among these problems is that the concentration of air pollutant varies spatially and temporally and the conditions of trees are highly variable within a city. Large samples are needed to account for this variation. Another approach to determine the air pollution reduction effect of trees in urban areas is to integrate the knowledge of meteorology and atmospheric chemistry with tree biology to model air pollution reduction in a certain area and time. This method was used by Nowak (1994a), Nowak and Dwyer (2000) and Scott et al. (1998) to study several American cities. Their studies show that urban forest can contribute significantly to air pollution reduction. There are some uncertainties and limitations in this modeling method that need to be improved. Scott et al. (1998) gave a detailed discussion of these limitations. The main limitation of this method is that the direct air pollutants reduction by trees is calculated using a "big-leaf" model. The air pollutant concentration was assumed as homogenous in whole city, and the trees were assumed as occurring in a homogeneous, connected layer. In reality, the urban building configuration, the local photochemical reaction, and the meteorology condition influences the air pollutants concentration in a city resulting in a somewhat less than homogenous concentration. Also, the trees vary with different heights and crown configurations. So the air pollutants deposition rate estimated using a "big-leaf" model is only a rough approximation of the real situation. However, the method is still the best available method and was used in this study.

Trees in urban areas also work to sequestrate CO_2 from the atmosphere and store it in the form of woody biomass. Because of its role as a greenhouse gas in global warming, the reduction of CO_2 levels in the atmosphere was defined as an important task in the Kyoto Treaty. Furthermore, urban forest helps to reduce energy use for cooling and heating, resulting in the reduction of CO_2 emission from power plants (McPherson and Simpson, 1999).

Studies on the structure of the urban forests in Beijing and its role in air pollution control are limited. Zhu and Wu (1995) studied the pattern of roadside greenspace. Zhang (2001) studied species diversity. Zhao et al. (2001) conducted investigations on street tree planting. Profous (1992) studied the influence that management practice, nursery production, public preference, historical development and land use had on the urban forest structure in Beijing. Chen et al. (1998) conducted the most comprehensive studies to date on the Beijing greenspace and its ecological benefits. They studied the distribution, structure and management of greenspace in Beijing. Also, they estimated CO_2 sequestration, absorption of SO_2, chlorine gas (Cl_2), dust interception, and the influence of evapotranspiration from vegetation on air temperature by plants in the Beijing greenspace. However, their study did not provide the fundamental characteristics of the urban forest such as the DBH (the diameter of tree at the breast height) class distribution, the species percentage, and health conditions of the trees. In their studies of CO_2 sequestration and reduction of air pollution Chen et al. (1998) extrapolated field measurements from about dozens trees of 21 species to the entire city. As mentioned before, this method neglects the spatial and temporal change of air pollution concentration. It also does not account for the variations in different species, different growth habit and differences in tree condition in different part of the city.

The study presented here was designed to provide a more detailed analysis of the Beijing urban forest and its effect on air pollution. Four objectives were addressed in the study: (1) to describe the current composition and structure of the Beijing urban forest; (2) to quantify the major air pollutants including SO_2, NO_2, PM_{10}, and O_3 that are reduced from the atmosphere by urban forest; (3) to quantify the BVOC emission from the urban forest; (4) to calculate the sequestration of CO_2.

Material and methods

Study area

Beijing, the capital city of China, lies on the northern edge of the North China Plain, between longitudes 115°25–117°30 E, and between latitudes 39°28–41°25 N. It is flanked on the north and west by the Jundu Mountain and Xi Mountain, rising to about 2000 m above sea level. The average elevation of mountainous area is over 1000 m. The mountain descends into a foothill area and then to the small Beijing plain. Sixty-two percent of the area of Beijing administration area is hilly. The lowlands in the southeastern part of the Beijing plain are less than 100 m high, mostly 30–50 m. These lowlands are the most intensively developed areas of Beijing. The area administrated by the Beijing municipal government is 16,807 km^2. The administration area is composed of four city districts, four suburb districts and two outer suburbs, as well as 8 rural counties. Traditionally, the four city districts (Xuanwu, Xicheng, Chongwen, and Dongcheng) plus parts of four suburban districts (Haidian, Shijingshan, Fengtai and Chaoyang) are viewed as the central city. The area of the central city is about 300 km^2. This study focused on the central city (Fig. 1).

Beijing is located on the eastern rim of the Eurasian land mass and belongs to the West Wind Belt. It is characterized by a warm temperate continental monsoon climate. The four seasons are quite distinct. The annual average temperature is 11.5 °C, with an average precipitation of 630 mm, about 70% of which is concentrated in July August. On the lowlands, the frost-free period is 190–195 days (Victor, 1995).

According to the census of 2000, the population of Beijing was 13.8 million. About 4.5 million of people live in the study area. In the four city districts, the population density is very high. The highest density, 32,486 people/km^2, occurs in the Xuanwu district, the lowest density with 24,614 people/km^2 in the Xicheng district. In the four suburban districts, the population density is lower but on average it reaches 3523 people/km^2 (Beijing Bureau of Statistics 2004).

Research method

The method used in this study to determine different urban cover types involved an estimation of the area of the types on satellite image and a field survey conducted to measure structural parameters of the Beijing urban forest.

Satellite image acquisition and analysis

One scene of Landsat ETM + Level G images taken on 05/22/2002 with path 123, row 32 covering the Beijing region was obtained from EROS Data Center. The study area was cut out from the image. During preprocessing, band 8 was merged with 6 visible/IR bands. A SAVI band was calculated using the equation:

$$\text{SAVI} = \left[\frac{(\text{NIR} - \text{VISred})}{(\text{NIR} + \text{VISred} + L)}\right](1 + L), \qquad (1)$$

where NIR is band 4, VISred is band 3, and L, designed to correct for the soil reflectance component of energy detected by the sensor, is equal to 0.5 (Huete, 1988). After preprocessing, the image was analyzed using unsupervised classification. The ISODATA procedure was adopted. Twenty classes and 50 iterations were used to run ISODATA. After running the ISODATA procedure, the clusters formed were merged into meaningful classes by referring to the original image. An accuracy assessment with 100 randomly distributed checking points on original satellite image in each class was conducted.

Field survey

A field survey was conducted in June 2002. A stratified random sampling method similar to that of Nowak (1994a) and McPherson (1998b) was applied. Stratified random sampling has the following advantages: (a) increases precision over simple random sampling, (b) produces separate estimates for each stratum, and (c) reduces the sampling cost and time. Another purpose of using this method was to facilitate comparisons between Beijing and the cities Nowak and McPherson had studied. The study area in Beijing was divided into three strata based on the developmental history of the city:

(1) *Old city*: the area contained within the second ring road which was the city of Beijing before 1949.
(2) *Third ring road area* (TRRA): the area between the second ring road and the third ring road, which mainly developed between 1950 and in 1980.
(3) *Fourth ring road area* (FRRA): the area between the third ring road and the fourth ring road. This area mainly developed after 1980.

The urban forest within each area was assumed to be relatively uniform but distinct from the other areas because of the similarity of developmental history and construction style in each area.

Two hundred and fifty sampling plots were located in the entire study area. The total number of plots was decided by referring to the number used by Nowak (1994a, 213 plots for an area of 603 km^2, Chicago, IL), McPherson (1998b, 244 plots for an area of 236 km^2, Sacramento, CA). Based on Nowak's experiment, 200 sampling plots in a city can result a standard error of 10% (Nowak et al., 2003). The distribution of sampling

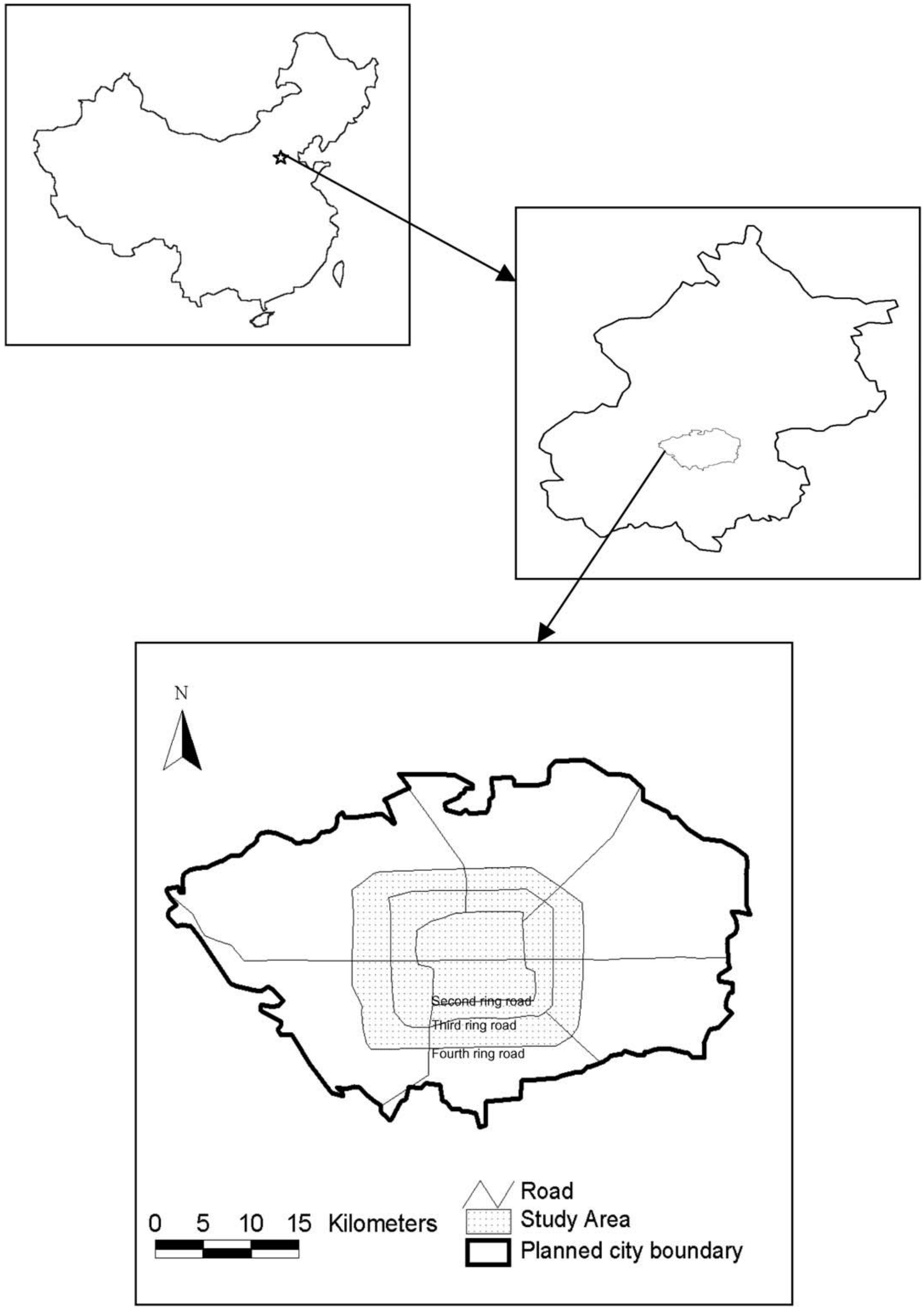

Fig. 1. Upper left figure shows the location of Beijing in China. Figure in the middle shows the Beijing administration area and the position of the area that is designed as the city part of Beijing by the master plan. The lower figure shows the ring roads (old city = area inside the second ring road; TRRA = area between second and third ring road; FRRA = area between third and fourth ring road) and the total study area.

plots among areas was proportional to the amount of tree/shrub cover in each area determined from the satellite image analysis. The plots were located on the 2.5 m resolution color orthophotos taken in 2000 by randomly picking X and Y for each sampling point from a coordinate system lay over the photos.

On the ground, once a plot center was located with the help of the aerial photos, a circular plot with a radius of 11.3 m was set up. The area of each plot was approximately 400 m^2. The information listed in Table 1 was collected or measured on each plot.

The land use of the plot was recorded in following way: if the plot was located in a single land use category (e.g. residential), then that land use type was recorded. If the plot was located on two or more land use categories, the percentage of each land use category in the plot was recorded. Tree cover measures the percentage of the area of the plot covered by tree crown and was estimated visually. On the ground, the percentages of the surface area of the plot covered by different land cover types listed in Table 1 were estimated and recorded. Whenever possible tree identification to the species level was made on the site. If a species could not be identified in the field, a sample was collected, labeled and later identified by using an identification key to trees of the Beijing region (Chen, 2003) or by consulting local arboriculturist. The DBH of trees were measured with a DBH tape at a height of 1.35 m above the ground for single stem trees. If a tree had multiple stems, the DBH of each stem was measured and recorded. DBH was measured to the nearest 0.1 cm. The height of each tree was measured by using a SUUNTO clinometer to the nearest 0.1 m. The height from ground to the lowest living branch of the tree was also measured to give the bole height of the tree. The crown width of each tree was measured along north to south and east to west diameters of the crown. The average of these two measurements was used to represent the crown width of that tree. The percentage of any normal live crown that was missing was estimated as the part of the crown if the tree had grown to its full crown shape. The health condition of trees was classified into seven categories: Excellent, no obvious dead branches inside tree crown; Good, 1–10% of crown composed of dead branches; Fair, 11–25%; Poor, 26–50; Critical, 51–75%; Dying, 76–99%; Dead, 100%. (Adopted from Nowak et al., 2003).

Table 1. Information collected on sample plots for the Beijing urban forest

Plot information	Land use Tree cover
Ground cover information (percentage covered by each type)	Buildings Cement surface Other impervious[a] surface material area (e.g. brick) Soil surface Shrub cover Grass cover Herbaceous cover (other than grass) Water surface
Tree information	Species DBH Height Height to live crown Crown width Percent of normal live crown that is missing Health condition

[a]Impervious surface includes ground surface covered by building, asphalt, concrete, rock and other surface that prevents the infiltration of water.

Urban forest parameters calculation

The following formulas were used to calculate the parameters of the urban forest (Nowak, personal communication):

$$T = \sum_{r=1}^{3} T_r, \tag{2}$$

$$\mathrm{var}(T) = (A^2)\mathrm{var}(M_{\mathrm{area}}), \tag{3}$$

where T is the estimation of the total value of an urban forest parameter (e.g. number of trees, carbon storage) for the entire study area. T_r is the estimation of the total value of an urban forest parameter for a specified stratum. A is the total area of the entire study site. M_{area} is the estimated urban forest variable for the entire study area on a per area basis (e.g. number of trees per hectare). T_r is calculated as

$$T_r = \left(\frac{A_r}{a_r}\right)\bar{y}_r, \tag{4}$$

$$\mathrm{var}(T_r) = \left(\frac{A_r}{a_r}\right)^2 \mathrm{var}(\bar{y}_r), \tag{5}$$

where A_r is the area of one specific stratum, a_r is the area of a sampling plot, $\bar{y}_r$ is the sample mean of an urban forest parameter in a stratum (e.g. number of tree, leaf surface area, biomass volume). $\bar{y}_r$ is calculated as follows:

$$\bar{y}_r = \left(\sum_{i=1}^{n} y_{ri}\right) \Big/ n, \tag{6}$$

$$\mathrm{var}(\bar{y}_r) = \left[\frac{(1-f)}{n}\right] s^2(y)_r, \tag{7}$$

where y_{ri} is the sampled urban forest parameter in a sample plot, n is the total number of sample plots in one stratum. f is the portion of area sampled in a stratum. $s^2(y)_r$ is the sample variance of an urban forest parameter y. It is calculated as

$$s^2(y)_r = \frac{\sum_{i=1}^{n} \left(y_{ri} - \bar{y}_r\right)^2}{n-1}. \tag{8}$$

$\mathrm{var}(M_{\mathrm{area}})$ is calculated as

$$\mathrm{var}(M_{\mathrm{area}}) = \left[\sum_{r=1}^{3} A_r^2[\mathrm{var}(M_r)]\right] \Big/ A^2, \tag{9}$$

$$\mathrm{var}(M_r) = \left(\frac{1}{a_r}\right)^2 \mathrm{var}(\bar{y}_r). \tag{10}$$

Air pollution reduction calculations

Trees with their dense leaves, twigs, and branches, construct a rough aerodynamic surface. Their surface is very effective for direct removal of the air pollutants from the air through the dry deposition process (Beckett et al. 1998).

The removal of a particular air pollutant at a given place over certain time period then was calculated as (Nowak, 1994a)

$$Q = F \times L \times T, \tag{11}$$

Q is the amount of a particular air pollutant removed by trees in a certain time, F is the pollutant flux, L is the total canopy cover in that area, and T is the time period. The pollutant flux F is calculated as (Nowak, 1994a)

$$F = V_{\mathrm{d}} \times C, \tag{12}$$

V_{d} is the dry deposition velocity of a certain air pollutants, and C is the concentration of a particular air pollutant in the air. The dry deposition process can be described as (Nowak, 1994a)

$$V_{\mathrm{d}} = \frac{1}{R_{\mathrm{a}} + R_{\mathrm{b}} + R_{\mathrm{c}}}, \tag{13}$$

V_{d} is the dry deposition velocity, R_{a} the aerodynamic resistance, R_{b} the quasi-laminar boundary layer, and R_{c} is the canopy resistance. R_{a}, R_{b}, R_{c} was calculated as (Killus et al., 1984)

$$R_{\mathrm{a}} = \frac{u(z)}{u_*^2}, \tag{14}$$

$u(z)$ is the wind speed at height z; u_* is the frictional velocity, and is expressed as the dimensionless ψ_{m} stability function for momentum

$$u_* = \frac{ku(z-d)}{\ln[(z-d)/z_0] - \psi_{\mathrm{m}}[(z-d)/L] + \psi_{\mathrm{m}}[z_0/L]}, \tag{15}$$

where k is the von Karman's constant (0.4), d the displacement length (8 m) and z_0 the roughness length (0.5 m), and L the Monin–Obukhov stability length. L was estimated by classifying local meteorological data into stability classes using Turner classes (Panofsky and Dutton, 1984) and then estimating $1/L$ as a function of stability class and z_0 (Zannetti, 1990).

When $L<0$: unstable condition (van Ulden and Holtslag, 1985):

$$\psi_{\mathrm{m}} = 2\ln\left[\frac{(1+X)}{2}\right] + \ln\left[\frac{(1+X^2)}{2}\right] - 2\tan^{-1}(X) + 0.5, \tag{16}$$

where the dimensionless factor X was calculated as (Dyer and Bradley, 1982)

$$X = \left(1 - 28\frac{z}{L}\right)^{0.25} \tag{17}$$

when $L>0$: stable condition

$$\psi_{\mathrm{m}} = -17\left[1 - \exp\left(-0.29\frac{(z-d)}{L}\right)\right] \tag{18}$$

R_{b} was calculated as (Pederson et al., 1995)

$$R_{\mathrm{b}} = \frac{2S_c^{2/3} \times P_r^{-2/3}}{ku_*}, \tag{19}$$

where k is the von Karman constant, S_c the Schmidt number, and P_r is the Prandtl number.

During the growing season, hourly tree-canopy resistances R_{c} for O_3, SO_2, and NO_2 are calculated based on a multi-layer canopy deposition models (Baldocchi et al., 1987; Baldocchi, 1988). Hourly inputs to calculate canopy resistance are photosynthetic active radiation (PAR), air temperature, wind speed, u_*, carbon dioxide concentration, and absolute humidity. For PM_{10}, its deposition velocity was assumed to be $0.0064\,\mathrm{m\,s^{-1}}$ for growing season and $0.0014\,\mathrm{m\,s^{-1}}$ for the leaf-off season, a 50% resuspension rate for PM_{10} back to the atmosphere was assumed. Monthly and yearly removal of NO_2, O_3, PM_{10}, and SO_2 by trees and shrub in Beijing were calculated using the Urban Forest Effects model (UFORE) developed by the USDA Forest Service, Northeastern Research Station, which incorporated these algorithms into one software package (Nowak and Crane, 2000). Daily air pollution data including NO_2, SO_2, O_3, and PM_{10} concentration in the atmosphere of Beijing in 2002 was obtained from the Beijing Environmental Protection Administration. Daily meteorology data for the same year monitored by a weather station located in Beijing was also acquired. These data were inputs required for running the UFORE model.

Urban forest modifies the micro- scale climate mainly through: (1) direct shading, (2) evapotranspiration, and (3) wind speed reduction. In Beijing, the main building type is the high-rise building. Through the field survey, the typical height of building was 16–66 m. Direct shade by trees is not very effective in reducing energy use for large buildings and the wind speed reduction effect of trees on energy use for high-rise buildings is not clear (Simpson, 1998). Therefore, the effects of shading and wind speed reduction were not included in this study. The effect of indirect air pollution reduction was calculated as the emission avoided by reducing the energy used for cooling in the summer due to evaporation.

The temperature reduction by evapotranspiration was the main influence of the urban forest on climate considered in this study. The cooling effect was calculated by using Eq. (20), modified from Simpson (1998):

$$E = E_t \times T_c \times A_c, \quad (20)$$

where E is the total electricity saving from air temperature modification by trees, E_t is the electricity usage saving from one unit air temperature change, T_c is the air temperature change caused by percent canopy cover increase, and A_c is the total canopy area in the study area.

In this study, E_t was assumed to be a reduction of 7% of energy used for air conditioning per degree air temperature change, and T_c was assumed to be 0.1 °C for each percentage increase in canopy cover (Simpson, 1998). Detailed discussion of these values can be found in Simpson's article.

In 2002, according to the statistics by the Beijing public utility company, the total power used by air conditioning in Beijing was 7 million kW/h, of which about 3 million kW was running regularly. The average annual air condition use time is about 1000 h in Beijing. So the total electricity used for air conditioning in Beijing was estimated as 3 GWh for the year 2002. Air conditioning usage in the rural population of Beijing was assumed to be negligible, and the average air conditioning usage per capita was assumed to be equal in all parts of the city. Therefore the electricity used for air conditioning in study area was calculated by multiplying the total electricity used for air conditioning by the ratio of the population in the study area to all population in the city sector, that is 9/13. The electricity used for air conditioning in study area was then calculated to be 2 GWh.

The release of BVOCs was calculated. The major BVOC that contributed to ozone formation are isoprene and monoterpene. The standard isoprene and monoterpene emission rate of each tree species was adopted from Benjamin et al. (1996), Benjamin and Winer (1998), and Wang et al. (2003). Emission of BVOC from plants is restricted by air temperature and solar radiation. The algorithm developed by Geron et al. (1994) was used to modify the emission rate based on meteorological conditions. The emission of isoprene and monoterpene by individual trees was calculated by multiplying the emission rate with the total leaf biomass of that tree. The total leaf biomass was calculated using a regression equation developed by Nowak (1996). The total BVOC emission from the whole urban forest was the sum of the emission of individual trees.

The contribution of BVOC to O_3 formation was also simulated. A maximum incremental reactivity (MIR) scenario was assumed for forming ozone from BVOC, which assumes that NO_x and meteorological conditions were not limiting factors in the ozone production. The MIR scale (MIRs) for isoprene and monoterpene was adopted from Carter (1994). They are 9.1 g ozone/g isoprene emitted, and 3.3 g ozone/g monoterpene emitted, respectively. However, it should be noticed that the calculated ozone formation is not the reality. It only shows the maximum potential of ozone production if all conditions for ozone production are ideal. In reality, this is a complicated process that remains hard to quantify.

Carbon dioxide storage and sequestration

Carbon stored in tree biomass was estimated using published tree biomass equation (Chen et al., 1998; Nowak, 1994b). The information on species, diameter, and tree height collected during field survey was used as input. If an equation for one species could not be found, the equation for a similar species in the same genus was used. The result was expressed as fresh-weight biomass for the above ground part of trees. The result was multiplied by 1.22 to derive the biomass for the whole tree (Nowak, 1994b). The all tree biomass for conifer and broadleaf were then multiplied by 0.56 and 0.48, respectively, to calculate the dry weight (Nowak, 1994b). Dry weight was converted to carbon storage estimation by multiplying a C coefficient of 0.50. To adjust the biomass estimation based on equations derived for forest trees to open-grown urban trees, the final carbon storage was reduced by 20% (Nowak, 1994b).

Annual carbon sequestration was estimated by calculating the difference between the carbon stored by the current urban forest and that stored by the urban forest 1 year older than the current one. The annual growth rates of trees were adopted from Nowak (1994b). A mortality rate of 5% was assumed for current forest after consulting the local forester. No carbon sequestration was calculated for dead trees.

Results

Structure of Beijing urban forest

The results of the analyses of land cover composition of the study area are shown in Table 2. The overall accuracy of classification was 74.5%, and the Kappa coefficient was 0.69. The classification accuracy was not high because the traditional classification method cannot solve the mixing pixels problem in urban environment very well.

The percentages in Table 2 are the perpendicular projection of the various land cover types interpreted

Table 2. Land cover composition in study area in Beijing

Sector	Land area (ha)	Tree/shrub (%)	Grass/ herbaceous (%)	Impervious area (%)	Bare soil (%)	Water (%)
Old city	6188.3	21	5.4	67.5	1.5	4.6
TRRA	9726.5	20.2	7.3	66.7	2.9	2.9
FRRA	14,206.2	11.8	9.8	70.6	6	1.8
Study area	30,121.0	16.4	8.1	68.7	4.1	2.7

Table 3. Land area, tree number, tree density and canopy cover (standard error in parentheses) in sectors of Beijing

Sector	Land area (ha)	Estimated tree number (thousand)	% of total trees	Tree density (no./ha)	Canopy cover (%)
Old city	6200	488 (67)	20	79 (11)	25
TRRA	9676	524 (91)	22	54 (9)	14
FRRA	14,304	1371 (269)	58	96 (19)	12
Study area	30,180	2383 (291)	100	79 (10)	17

from the satellite image. Overlap of different land covers was not counted. For example, the shrub layer and grass layer under tree canopy were not counted because they could not be seen from the photos. From the table, it is clear that the impervious surface is the dominant land cover type of Beijing, which is reasonable because of the high population density in Beijing.

Of the 250 plots initially selected for sampling, only 204 plots (82%) were actually sampled. Most of the unsampled plots were located on sensitive government agency land where access was denied. It is possible the total number of trees was underestimated because government land usually has high tree cover. The analyses of the 204 sample plots indicated approximately 2.4 million trees in the study area (see Table 3).

The fourth ring road area had the most trees and also the highest tree density. Conversely, the greatest canopy cover occurred in the old city. This difference in canopy cover was mainly due to the large size trees in the old city.

Forty-five tree species and 33 shrub species were found on the sampled plots in this study. Official record (Beijing Annals Editorial Board 2000) shows that there are about 170 tree species used in landscape planting in Beijing. The difference largely resulted from the fact that the official record also includes species grown in nurseries.

The most common tree species found in study area were *Sophora japonica* L. and *Populus tomentosa* Carr. (Table 4). They are the most common street tree species and they are also widely used as landscape trees on institutional land (e.g. government agencies, schools) and residential areas because of their tolerance to compacted soil, air pollutants, and drought (Chen et al., 1983). These two species are still being used in new planting programs today. Other species that were widely distributed include *Robinia pseudoacacia* L. and *Fraxinus chinensis* Roxb.

Table 4. Number (standard error in parentheses) and percentage of total trees for the top 10 tree species in the entire study area in Beijing

Species	Estimated number (thousand)	Percentage
Sophora japonica L.	502 (227)	21
Populus tomentosa Carr.	381 (77)	16
Juniperus chinensis L.	277 (81)	12
Robinia pseudoacacia L.	192 (73)	8
Fraxinus chinensis Roxb.	96 (35)	4
Sophora japonica L. cv. Pendula	84 (42)	4
Pinus tabulaeformis Carr.	83 (53)	3
Populus canadensis L.	75 (22)	3
Ailanthus altissima (Mill.) Swingle.	74 (24)	3
Ginkgo biloba L.	71 (27)	3

The diameter distribution represented an age distribution if one assumes that older tree will have larger diameters when grown under the same environment conditions and management scheme as younger trees (Fig. 2). Based on that assumption, the Beijing urban

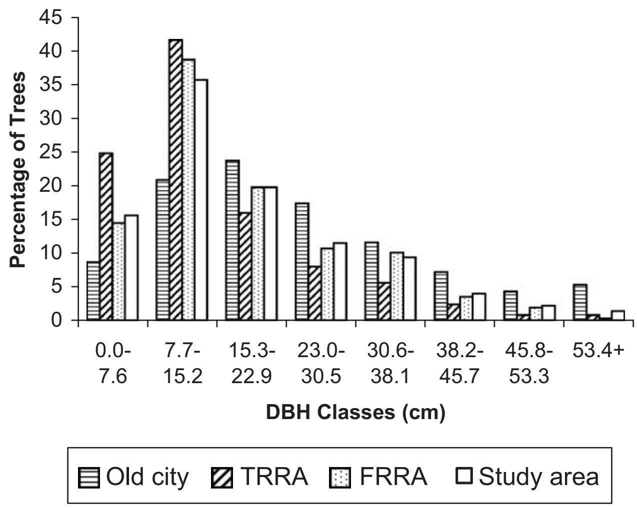

Fig. 2. Distribution of trees by DBH classes for each sector and the entire study area (see Fig. 1).

forest may be characterized as an all-age forest dominated by younger age classes.

The ranking of tree health condition suggests that about 40% of the trees in the study area were in good and excellent condition, 31% in fair condition, and 29% in poor, critical, dying and dead condition.

Carbon dioxide sequestration and air pollutants removal

The urban forest in study area stored about 224,000 tons of carbon in biomass form (Table 5).

The FRRA had more trees than old city and the TRRA, so it also stored more carbon. However, due to the larger tree size in the old city, the average carbon storage per tree in FRRA was only 84.2 kg, while in the old city it was 162.6 kg.

The monthly average air pollutants concentration in Beijing is shown in Fig. 3.

The monthly average concentration shows that the main air pollutant in Beijing in 2002 was PM_{10}. It peaked in spring and leveled off thereafter. The concentrations of O_3 and SO_2 also have strong seasonal patterns. The concentration of ozone was highest in summer when the air temperature was high and the photochemical reaction was active. The concentration of SO_2 was highest in winter and lowest in summer, because coal is still the main fuel for winter heating.

The total annual air pollutant uptake by trees from the atmosphere was around 1261.4 tons (Fig. 4). Standardized pollution removal rate (g/yr per m^2 canopy cover) was 27.5. PM_{10} accounted for 61% of total air pollutants.

The largest air pollutant removal occurred in April (167.1 tons), and the lowest in November (43.8 tons) (Fig. 5). The removal rates showed a pattern close to the seasonal variation in the concentration of air pollutant and the biological cycle of trees. Taking PM_{10} as an example, the removal rate was higher in spring and lower in winter. The reasons are: (1) trees fully expand their foliage in late spring and the surface available for trapping particles increases; (2) the dry and windy climate in Beijing in spring increases PM_{10} concentration. The removal was lower in winter because the majority of tree species in Beijing are deciduous (76%). Even though the PM_{10} concentration in the air is higher in winter due to the burning of coal for heating, the loss of foliage reduces the ability of trees to intercept air pollutants. The small amount of air pollutant removal in winter is mainly due to conifers.

Table 5. Carbon storage and sequestration (standard error in parentheses) in the investigated sectors in Beijing

Sector	C Storage (thousand tons)	C Sequestration (thousand tons/ year)
Old city	79.3 (13.3)	3.5 (0.5)
TRRA	29.4 (6.3)	1.9 (0.3)
FRRA	115.4 (30.7)	6.0 (1.2)
Study area	224.2 (34.1)	11.4 (1.3)

By comparing the pollution removal rates in Beijing with that of several American cities (Fig. 6), the Beijing urban forest shows a higher removal rate, that may be due to the higher concentration of air pollutants.

The trees in Beijing emitted 201.7 tons of isoprene and 35.5 tons of monoterpene. The total ozone forming potential was 1952.6 tons. This number does not represent the real ozone formed because the urban center is usually thought of as "NO_x limited" and the formation of ozone is small due to a high VOC/NO_x rate (Benjamin and Winer, 1998). The NO_x emission in Beijing is increasing quickly because of the rapid increase of in the number of automobiles (Zhu and Jiang, 2002). Combined with the hot summer and the slow air mass movement caused by the topography of Beijing (Liu and Ren, 2003), the BVOC may contribute to the formation of ozone in the future because of its high photochemical reactivity (Chameides et al., 1988).

With a tree/shrub cover of 16.4%, the total air temperature decrease by current trees and shrubs was 1.6 °C. The air temperature decrease led to less air conditioning use. The total electricity saving by trees through lowering air temperature was calculated as 0.238 GWh.

In Beijing, about half of the electricity consumed is imported from outside producers, while the remaining is produced locally. The saved electricity was assumed to reflect this pattern. The total saved locally produced

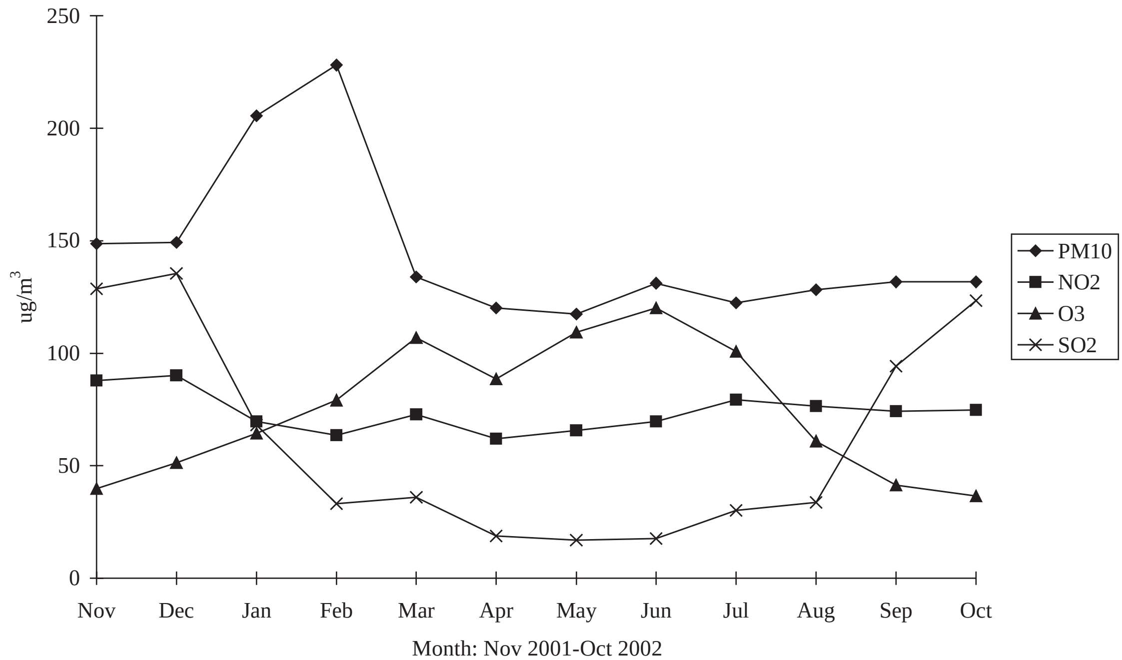

Fig. 3. Monthly average concentration of the major air pollutants in Beijing (based on data from Beijing Environmental Protection Administration).

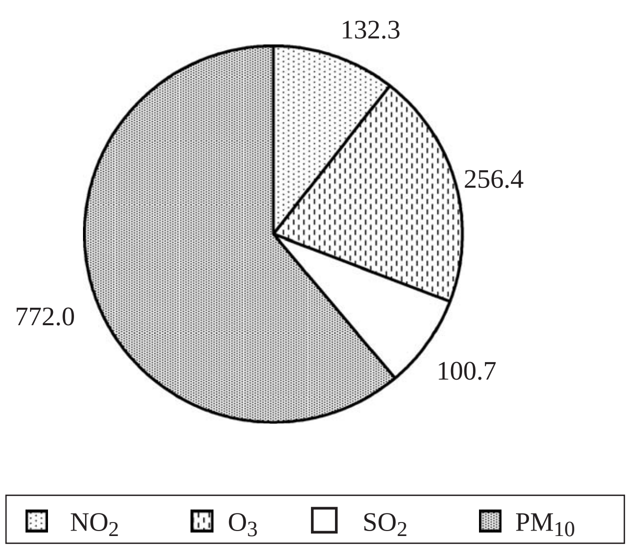

Fig. 4. Annual air pollutant removal by trees in the total study area in Beijing (unit: ton). The percentages of different air pollutants to total removal are NO_2 (11%), O_3 (20%), SO_2 (8%), and PM_{10} (61%).

electricity was therefore 0.119 GWh (Table 6). The main fuel type for power plants in Beijing is coal. For one kWh of electricity produced, 349 g of standard coal was consumed. According to a study by Energy-China (2004), burning of one ton of standard coal results in the emission of 20 kg SO_2, 7 kg NO_x, 15 kg total suspended particles (TSP), and 440 kg CO_2. The air pollutant emission avoided through reducing the cooling energy use is shown in Table 6.

The CO_2 emission avoided is about 44% of the amount of CO_2 sequestrated by tree, which is 11373 ton C/year (converted to CO_2, it is about 41701 tons/year).

Discussion

The current size structure of the urban forest in Beijing is not optimal for air pollution removal. Sixty percent of the trees are still too small to provide considerable air pollution removal. According to Nowak (1994a), a large tree with a diameter of 76 cm can remove 70 times more air pollutants from the air in Chicago than a tree with a diameter of 8 cm. We recommend the preservation of existing trees, rather than the transplanting or removal of many existing trees that is currently taking places in Beijing. Developers should be required to incorporate existing trees into development plans. Buildings require 1 or 2 years for their construction but trees need 20–30 years to grow up to a fully functional size.

Another factor that reduces the efficiency of air pollutant uptake by trees in Beijing is the heavy pruning practice (Yang and McBride, 2003). Trees with large canopies can intercept more air pollutants than trees with smaller canopies.

The current species composition in Beijing is also not ideal for air pollutant removal and CO_2 sequestration.

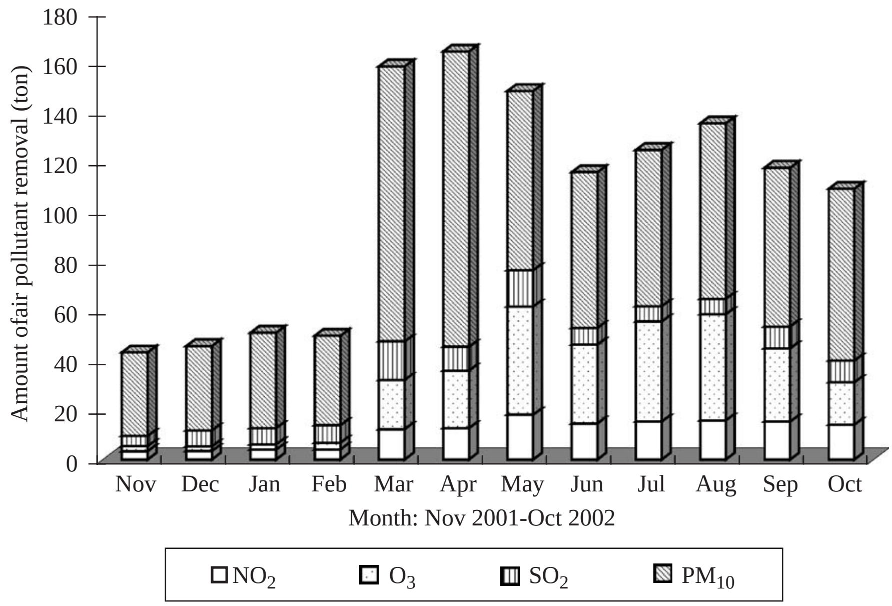

Fig. 5. Monthly air pollutant removal by trees in the total study area in Beijing.

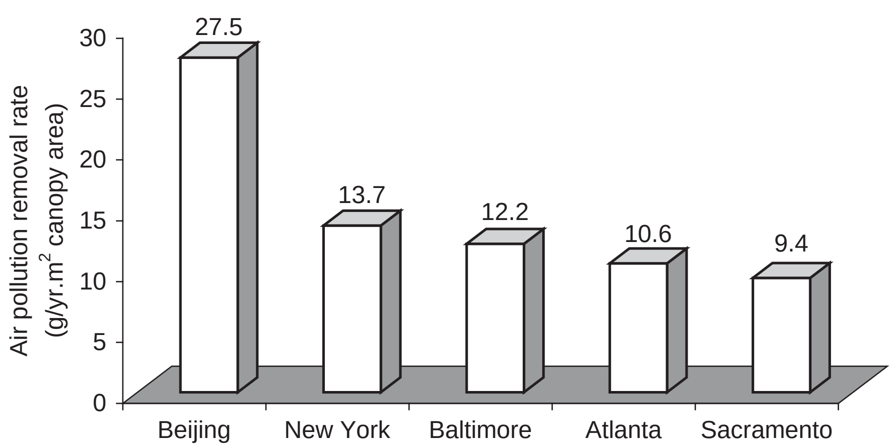

Fig. 6. Standardized air pollution removal rate in Beijing and a few American cities (McPherson and Simpson, 1998; Nowak, 2004).

Table 6. Air pollutants emission avoided by reducing the energy use for air conditioning by means of the urban trees in Beijing

Total electricity saved (GWh)	Coal to electricity efficiency (g/kWh)	Total standard coal saved (thousand ton)	Air pollutants emission avoided (ton)			
			SO_2	NO_x	TSP	CO_2
0.119	349	41.6	832.1	291.2	624.1	18,306.7

Populus, *Robinia* and *Salix* are among the dominating genera; they have high BVOC emission rates (Benjamin and Winer, 1998) and therefore a high potential for increasing ozone formation. Moreover, these genera are fast growing and have relatively short life spans. The CO_2 fixed wood biomass in these genera will be released back to atmosphere sooner than it would if trees known for longevity, such as *Juniperus* spp. were planted. For future planting in Beijing, species should be chosen based on their suitability for the urban environment and their air pollutant removal ability. Factors to consider for are shown in Table 7.

Table 7. Criteria for selecting species in future planting program

Air pollutants removal ability	Suitability for urban environment
Type of trees (evergreen/ deciduous)	Pest and disease tolerance
Dimension (mature height, crown size)	Tolerance to various soil condition
Growth rate	Adaptation to the climate
Leaf characteristics	Tolerance to drought
Air pollution tolerance	Longevity
BVOC, pollen emission potential	

The rational for the criteria of air pollutant removal ability are:

(1) usually evergreen trees have higher efficiency in removing air pollutants because of their longer time of foliage retention (Beckett et al., 2000a);
(2) the tree's dimension determines the amount of CO_2 that the tree can store (Nowak et al., 2002), and the surface area for air pollutant interception and deposition (Beckett et al., 2000b);
(3) growth rate influences the annual CO_2 sequestration and the size of the functional crown surface for air pollutants removal. Fast growing trees usually began to sequestrate CO_2 early and could provide a surface for air pollutants soon after established (Nowak et al., 2002). However, this feature should be balanced with the longevity of species to prevent early turnover of sequestrated CO_2;
(4) the leaf characteristics will influence the deposition of air pollutants on leaf surfaces. Research indicated that leaves with hairy, resinous, scaly, and coarse surfaces could capture more particles than smooth leaf (Beckett et al., 1998, 2000a, b);
(5) if a tree is sensitive to certain air pollutants, it cannot be used at a site close to the source of the air pollutant;
(6) trees with high BVOC and pollen emission rate should be avoided in planting to improve the net air pollution reduction benefit of the urban forest.

Species are not only chosen for their ability to remove air pollutants, they must be chosen for their suitability to grow in urban environments. Suitability to grow in urban environment depends on a number of factors (Table 7). These include:

(1) high resistance to disease and insects because of the restriction of using pesticide in high population density areas;
(2) species must have the ability to tolerate the unique features of the urban soils, such as high compaction, low aeration and infiltration conductance, low nutrients supply, etc. (Craul, 1994);
(3) trees selected for future planting programs must be adapted to the local climate;
(4) trees in cities normally face an imbalance of water supply and consumption (Whitlow and Bassuk, 1988; Whitlow et al., 1992) -trees that cannot tolerate drought will have difficult in growing in most urban environments;
(5) longevity of the species is important for the sustainability of an urban forest, if trees with a short life span are used widely, the removal and replacement costs over a longer time period can be very high. Also, the CO_2 fixed in the form of biomass will soon be released back to atmosphere (Nowak et al., 2002).

There are three aspects of research on the reduction of air pollution by the Beijing urban forest that merit further study: (1) Uncertainty analysis of the result produced by the current model. Because the removal of air pollutants from the atmosphere by trees involves many complicated processes, such as the dispersion of air pollutants at different scale and the physiological change of trees influenced by meteorological conditions, uncertainty can result from combinations of these factors. Thus the results presented here are only an approximation rather than an accurate estimation of actual pollution removal. They should be used in cautious. Uncertainty analysis was beyond the scope of this study but will be pursued in next stage of research. (2) Measurement of the air pollutants removal by individual trees. The uncertainties imbedded in the use of estimations of air pollutants uptake by individual species could be reduced by actual air pollutant uptake measurement. These measurements can also be used to refine the assumption in the UFORE model that the trees act as a homogeneous connected layer (Scott et al., 1998). Field measurement of the reduction of gaseous pollutants by different species could also refine the current model that is solely based on deposition rate of the pollutants. (3) Accurate modeling of the air pollution concentration and its relation to the location, size, and species composition of the urban forest to generate better estimation of pollution reduction. Detailed air pollutants dispersion models like the urban dispersion modeling system (UDM; Karppinen et al., 2000) could be modified and integrated with the UFORE model. This could produce detailed, site specific air pollutants concentration and uptake by trees in the urban area by using detailed tree information generated from high spatial resolution satellite images.

With all these limitations in mind, the result still shows that the urban forest in Beijing has a potential to reduce the air pollutants from the atmosphere. Thus tree planting can be used as an effective way in alleviating the air pollution problems in Beijing. This desired benefit of urban forest could be further enhanced by adopting our recommendations on careful species selection and better management practice.

Acknowledgement

We want to express our gratitude to Dr. David Nowak in USDA, of the Forest Service. He generously provided the UFORE software and patiently guided us through it. We also want to thank two anonymous reviewers for their suggestions on improving the quality of this paper. Finally, we want to thank the graduate students at the College of Landscape and Gardening, Beijing Forestry University for their hard work in helping to collect field data in Beijing.

References

Akbari, H.S., Konopacki, S., 2004. Calculating energy-saving potentials of heat-island reduction strategies. Energy Policy, in press.

Baldocchi, D.D., 1988. A multi-layer model for estimating sulfur dioxide deposition to a deciduous oak forest canopy. Atmospheric Environment 22, 869–884.

Baldocchi, D.D., Hicks, B.B., Camara, P., 1987. A canopy stomatal resistance model for gaseous deposition to vegetated surfaces. Atmospheric Environment 21, 91–101.

Beckett, K.P., Freer-Smith, P., Taylor, G., 1998. Urban woodlands: their role in reducing the effects of particulate pollution. Environmental Pollution 99, 347–360.

Beckett, K.P., Freer-Smith, P., Gail, T., 2000a. Effective tree species for local air quality management. Journal of Arboriculture 26, 12–18.

Beckett, K.P., Freer-Smith, P., Gail, T., 2000b. The capture of particulate pollution by trees at five contrasting urban sites. Arboricultural Journal 24, 209–230.

Beijing Annals Editorial Board, 2000. Landscape plants. In: Beijing Annals Editorial Board (Eds.), Beijing Annals, Vol. 16 Municipal Administration, Copy 52, Gardens and Afforestation Annals. Beijing Publishing House, Beijing, China, pp. 337–384 (in Chinese).

Beijing Bureau of Statistics, 2004. Accessed on-line: http://www.bjstats.gov.cn/. Last accessed on 15/03/2004.

Benjamin, M.T., Winer, A.M., 1998. Estimating the ozone-forming potential of urban trees and shrubs. Atmospheric Environment 32, 53–68.

Benjamin, M.T., Sudol, M., Bloch, L., Winer, A.M., 1996. Low-emitting urban forests: a taxonomic methodology for assigning isoprene and monoterpene emission rates. Atmospheric Environment 30, 1437–1452.

Carter, W.L., 1994. Development of ozone reactivity scales for volatile organic compounds. Journal of Air & Waste Management Association 44, 881–899.

Chameides, W.L., Lindsay, R.W., Richardsen, J., Kiang, C.S., 1988. The role of biogenic hydrocarbons in urban phtotochemical smog: Atlanta as a case study. Science 241, 1473–1475.

Chen, Y.M., 2003. Landscape Trees. China Forestry Publishing House, Beijing.

Chen, Z.X., Zhou, Z.L., Li, Y.H., Li, J.L., 1983. Investigation of the suitability of tree species used in Beijing landscape planting. In: Chen, Z.X., Wang, Y. (Eds.), Research on Urban Landscape and Gardening (in Chinese).

Chen, Z.X., Su, X.H., Liu, S.Z., Gu, R.S., 1998. Research of the ecological benefits of greenspace in Beijing city. China Landscape and Gardening 14, 57–60 (in Chinese, with English summary).

Cowell, F.R., 1978. The Garden as a Fine Art: From Antiquity to Modern Times. Joseph, London.

Craul, P.J., 1994. Soil compaction on heavily used sites. Journal of Arboriculture 20, 69–74.

DeSanto, R.S., MacGregor, K.A., McMillen, W.P., Glaser, R.A., 1976. Open Space as an Air Resource Management Measure, Vol. III: Demonstration Plan. EPA-450/3-76-028b, US Environmental Protection Agency, St. Louis, MO.

Dochinger, L.S., 1980. Interception of airborne particles by tree plantings. Journal of Environmental Quality 9, 265–268.

Dyer, A.J., Bradley, C.F., 1982. An alternative analysis of flux gradient relationships. Boundary-Layer Meteorology 22, 3–19.

Energy-China, 2004. Monitoring, measuring, and auditing energy usage. Accessed on-line. http://www.energy-china.com/energy/save/jnjs/11456.html Last accessed on 15/03/2004.

Geron, C.D., Guenther, A.B., Pierce, T.E., 1994. An improved model for estimating emissions of volatile organic compounds from forests in the eastern United States. Journal of Geophysics Research 99 (D6), 12773–12791.

Huete, A.R., 1988. A soil adjusted vegetation index (SAVI). Remote Sensing of Environment 25, 295–309.

Karppinen, A., Kukkonen, J., Elolähde, T., Konttinen, M., Koskentalo, T., Rantakrans, E., 2000. A modelling system for predicting urban air pollution, model description and applications in the Helsinki metropolitan area. Atmospheric Environment 34, 3723–3733.

Killus, J.P., Meyer, J.P., Durran, D.R., Anderson, G.E., Jerskey, T.N., Reynolds, S.D., Ames. J., 1984. Continued Research in Mesoscale Air Pollution Simulation Modeling. Vol. V: Refinements in Numerical Analysis, Transport, Chemistry, and Pollutant Removal. EPA/600/3-84/095a, US Environmental Protection Agency, Research Triangle Park, NC.

Liu, X.Y., Ren, R., 2003. Characteristics and formation cause of air pollution in Beijing city. City and Disaster Reduction 1, 41–43 (in Chinese).

McPherson, E.G., 1998a. Atmospheric carbon dioxide reduction by Sacramento's urban forest. Journal of Arboriculture 24, 215–223.

McPherson, E.G., 1998b. Structure and sustainability of Sacramento's urban forest. Journal of Arboriculture 24, 174–190.

McPherson, E.G., Simpson, J.R., 1998. Air pollutant uptake by Sacramento's urban forest. Journal of Arboriculture 24, 224–234.

McPherson, E.G., Simpson, J.R., 1999. Carbon dioxide reduction through urban forestry: Guideline for professional and volunteer tree planters. Technical report, USDA, Forest Service, Pacific Southwest Research Station, Albany, CA.

Nowak, D.J., 1994a. Air pollution removal by Chicago's urban forest. In: McPherson, E.G., Nowak, D.J., Rowntree, R.A. (Eds.), Chicago's Urban forest Ecosystem: Results of the Chicago Urban forest Climate Project. USDA Forest Service, Northeastern Forest Experimental Station, Radnor, PA, pp. 63–81.

Nowak, D.J., 1994b. Atmospheric carbon dioxide reduction by Chicago's urban forest. In: McPherson, E.G., Nowak, D.J., Rowntree, R.A. (Eds.), Chicago's Urban forest Ecosystem: Results of the Chicago Urban forest Climate Project. USDA Forest Service, Northeastern Forest Experimental Station, Radnor, PA, pp. 83–94.

Nowak, D.J., 1996. Estimating leaf area and leaf biomass of open-grown deciduous urban trees. Forest Science 42, 504–507.

Nowak, D.J., 2004. The effects of urban trees on air quality. Accessed online: http://www.fs.fed.us/ne/syracuse/TREE%20Air%20Qual.pdf Last accessed on 20/03/2004.

Nowak, D.J., Crane, D.E., 2000. The Urban Forest Effects (UFORE) Model: quantifying urban forest structure and functions. In: Hansen, M., Burk, T. (Eds.), Integrated Tools for Natural Resources Inventories in the 21st Century. Proceeding of the IUFRO Conference. USDA Forest Service General Technical Report NC-212, North Central Research Station, St. Paul, MN, pp. 714–720.

Nowak, D.J., Dwyer, J.F., 2000. Understanding the benefits and costs of urban forest ecosystems. In: Kuser, J.E. (Ed.), Handbook of Urban and Community Forestry in the Northeast. Kluwer Academic/Plenum Publishers, New York, pp. 11–22.

Nowak, D.J., Kevin, L.C., Rao, S.T., Sistia, G., Luley, C.J., Crane, D.E., 2000. A modeling study of the impact of urban trees on ozone. Atmospheric Environment 34, 1601–1603.

Nowak, D.J., Stevens, J.C., Susan, M.S., Christopher, J.L., 2002. Effects of urban tree management and species selection on atmospheric carbon dioxide. Journal of Arboriculture 28, 113–122.

Nowak, D.J., Crane, D.E., Stevens, J.C., Hoehn, R.E., 2003. The Urban forest Effects (UFORE) Model: Field Data Collection Procedures. USDA Forest Service, Northeastern Research Station.

Panofsky, H.A., Dutton, J.A., 1984. Atmospheric Turbulence. Wiley, New York.

Pederson, J.R., Massman, W.J., Mahrt, L., Delany, A., Oncley, S., den Hartog, G., Neumann, H.H., Mickle, R.E., Shaw, R.H., Paw, U.K.T., Grantz, D.A., MacPherson, J.I., Desjardins, R., Schuepp, P.H., Pearson, J.R., Arcado, T.E., 1995. California ozone deposition experiment: methods, results, and opportunities. Atmospheric Environment 29, 3115–3132.

Profous, G.V., 1992. Trees and urban forestry in Beijing, China. Journal of Arboriculture 18, 145–153.

Scott, K.I., McPherson, E.G., Simpson, J.R., 1998. Air pollutant uptake by Sacramento's urban forest. Journal of Arboriculture 24, 224–234.

Simpson, J.R., 1998. Urban forest impacts on regional cooling and heating. Journal of Arboriculture 24, 201–214.

Taha, H., 1996. Modeling impacts of increased urban vegetation on ozone air quality in the South Coast Air Basin. Atmospheric Environment 30, 3423–3430.

Ulden, V.A.P., Holtslag, A.A.M., 1985. Estimation of atmospheric boundary layer parameters for diffusion application. Journal of Climate Applied Meteorology 24, 1196–1207.

Victor, F.S.S., 1995. Beijing: The Nature and Planning of a Chinese Capital City. Wiley, Chichester.

Wang, Z.H., Zhang, S.H., Lu, S.H., Bai, Y.H., 2003. Measuring the VOCs emission rate of plants in Beijing region. Environmental Science 24, 7–12 (In Chinese, with English summary).

Whitlow, T.H., Bassuk, N.L., 1988. Ecophysiology of urban trees and their management—the North American experience. HortScience 23, 542–546.

Whitlow, T.H., Bassuk, N.L., Deborah, L.R., 1992. A 3-year study of water relations of urban street trees. Journal of Applied Ecology 29, 436–450.

World Bank, 2000. China: Air, Land, and Water. The World Bank, Washington, DC.

Xiao, Q.F., McPherson, E.G., Simpson, J.R., 1998. Rainfall interception by Sacramento's urban forest. Journal of Arboriculture 24, 235–244.

Yang, J., McBride, J., 2003. A unique technique for street tree planting in Beijing. Arboricultural Journal 27, 1–10.

Zannetti, P., 1990. Air Pollution Modeling. Van Nostrand Reinhold, New York.

Zhang, Z.M., 2001. Problems of species diversity in Beijing landscape trees and solutions. Journal of Beijing Forestry University 23, 50–52 (In Chinese, with English summary).

Zhang, J.L., Zhou, J., Xie, S.D., Xie, X.Q., 2003. Study on the association between ambient air quality and daily death in Beijing. Journal of Environmental Health 20, 75–78 (In Chinese, with English summary).

Zhao, H.E., Liu, Z.H., Hu, D.Y., Dong, B.H., Chen, J.Y., 2001. Thoughts about development of street tree in Beijing. Journal of Beijing Forestry University 23, 65–67 (In Chinese, with English summary).

Zhu, Z.Y., Wu, S.Q., 1995. Investigation of roadside greenspace in Beijing. China Landscape and Gardening 1, 37–44 (In Chinese).

Zhu, S.L., Jiang, K.X., 2002. The energy needs and pollutants emission by Beijing city transportation in 1998–2020. China Energy 6, 26–31 (In Chinese).