Urban Ecosyst (2006) 9: 27–37
DOI 10.1007/s11252-006-5527-2

Carbon sequestration by *Quercus ilex* L. and *Quercus pubescens* Willd. and their contribution to decreasing air temperature in Rome

Loretta Gratani · **Laura Varone**

Abstract Carbon sequestration capability by *Quercus ilex* L and *Quercus pubescens* Willd., widely distributed in the city of Rome, and their contribution to decreasing air temperature were investigated. Crown volume is the most significant ($p < 0.01$) variable explaining variation of air temperature below the tree crown. *Q. pubescens* gives a higher contribution to decreasing air temperature during the hottest months, due to its inherent larger crown volume than *Q. ilex* (252 ± 19 and 533 ± 52 m^3, respectively for the large size). Moreover, our results show the existence of a strong urban carbon dioxide dome with a peak CO_2 concentration (on an average 432 ± 37 ppm) at polluted sites, 16% greater than at control sites. Total carbon sequestration is 84 ± 12 and 111 ± 9 Kg year^{-1} of CO_2 for the small *Q. ilex* and *Q. pubescens* tree size, respectively, and 151 ± 10 and 185 ± 7 Kg year^{-1} of CO_2 for the large *Q. ilex* and *Q. pubescen* tree size, respectively. *Q. pubescens,* by its higher total photosynthetic leaf surface area (39% higher than *Q. ilex*) and its higher mean yearly photosynthetic rates (48% higher than *Q. ilex*) seems to have a greater role than *Q. ilex*. However, taking into account the leaf longevity (i.e. 12 ± 3 months for *Q. ilex* and 4 ± 2 months for *Q. pubescens*), the evergreen species, by its continuous photosynthetic activity, contributes to reduce CO_2 throughout the year, and in particular during the winter months, when traffic volume has a pick, than *Q. pubescens*.

Keywords Carbon sequestration · "Heat island" · Tree structure · LAI · Evergreen and Deciduous species

Introduction

Urbanisation processes have increased pollution levels in urban areas which require long-term researche to understand the ecosystem dynamics, with particular attention to those urban systems of high historical and archaeological values (Gratani *et al*., 2000, 2003). The

---

L. Gratani ( )· L. Varone
Department of Plant Biology, University "La Sapienza", P.le A. Moro 5, 00185, Rome, Italy
e-mail: loretta.gratani@uniroma1.it

pollutants, when released into the atmosphere, pose a direct and serious hazard to living organisms in general, and to human beings in particular (Pearson *et al.*, 2000). In the last years, much attention has been focused on the atmospheric concentration of CO_2, which is a dominant greenhouse gas (Nowak and Crane, 2002). Humans and automobile activity produce more than 80% input of CO_2 into urban areas (Koerner and Klopatek, 2002). Moreover, CO_2 is site and time dependent (Nasrallah *et al.*, 2003; Gratani and Varone, 2005), and it is related to local weather conditions. Trees may improve the quality of urban life (Akbari, 2002; Brack, 2002) due to their large leaf areas, relative to the ground on which they stand. Depending on the structural properties of their leaf area, trees can act as biological absorbers or filters of pollutants (Gratani *et al.*, 2000, 2003; Pal *et al.*, 2002).

Trees act as sink for CO_2 by fixing carbon during photosynthesis and storing excess carbon as biomass (Nowak and Crane, 2002). Crown volume is a discriminant factor for carbon sequestration as leaf size and density. The partitioning of stored CO_2 for a typical forest tree is about 50% in trunk, 30% in branches and stems, and 3% in foliage (Birdsey, 1992). Increasing the number of trees in urban areas may potentially slow the accumulation of CO_2 atmospheric concentration (Moulton and Richards, 1990). Larger trees tend to extract and store more carbon dioxide from the atmosphere having a greater leaf area to trap air borne pollutants, cast shade, and intercept or slow rainfall run-off (Brack, 2002). Carbon dioxide increases air temperature through a "heat island" effect (Koerner and Klopatek, 2002): trees provide shade and their transpiration cools air beneath canopies, which can mitigate urban "heat island" and lower energy consumption for air conditioning (Akbari *et al.*, 1992).

The effects of humans and urbanisation on ecosystem processes can be better understood using urban ecosystems as a study tool in comparison with "control" sites (Groffman *et al.*, 1995; Gratani and Crescente, 1999; Gratani *et al.*, 2000).

This study aims to analyse the air amelioration capability of the city of Rome by the presence of trees. The city of Rome is characterised by (1) a high extension of the urbanised area, (2) the dominant role of expansion, (3) a high public and private means of transport movement, (4) a considerable value of archaeological presences, (5) a high volume of "green", (6) an historical centre of high historical value. Rome represents an example of a mega city where air pollution has increased in these last years causing risks to the health of the population. The urbanisation process in Rome has been increased during the last years. Many new suburban areas have been built by scaling down free areas surrounding the city, which is changing into a mega city (2.810.931 inhabitants, whose 32.569 are in the historical centre). Rome, from an administrative point of view, has a surface of 129.000 hectares of which 36.000 hectares are comprised in the highway ring that encircles the city (GRA). The territory is subdivided into agricultural areas (48%), built up areas (37%) and "green" areas (15%).

We would like to estimate the carbon sequestration capability by deciduous and evergreen tree species widely distributed in the city. Understanding the relationship among urban trees, people, and the environment can facilitate future urban designs that might enhance the environmental and social benefits from trees (Dwyer *et al.*, 1992).

Materials and methods

The study area

The study was carried out in the city of Rome (41°53′N 12°29′ E), characterised by a low altitude (the highest point is Mount Mario, 139 m on the sea level) (Zapparoli, 1997). From a geologic point of view, the physical environment of the city has been developed during the Pleistocene: the roman territory is comprised between two distinguished volcanic districts: to south—east the Albani Hills and to north—west the Sabatini Mountains, characterised mostly by explosive activity with magmas of alkaline—potassic type (Funiciello *et al.*, 1995).

The natural vegetation of the city is constituted from strips of persistent meadows of the suburban areas, trampled down environments, shrubs, ruderal or nitrophilous vegetation and fragments of deciduous and evergreen woods (Pignatti, 1995). The streets are characterised by tree species, in particular by *Q. ilex* (Gratani *et al.*, 1998; Gratani and Crescente, 1999).

The climate of Rome was of the Mediterranean type. The average total year rainfall was 659 mm; the average minimum air temperature during the coldest months (January and February) was $5.7 \pm 1.9\,^\circ\mathrm{C}$ and the average maximum air temperature of the hottest month (August) was $29.7 \pm 2.7\,^\circ\mathrm{C}$. Most of the total rainfall was distributed in autumn and the drought period was from June to August. The city was characterised by constant wind speed of $2.4 \pm 0.2\,\mathrm{m\,s^{-1}}$ during the year (data provided by the Meteorological Station of the Collegio Romano, for the period 1995–2003).

Field measurements were carried out during the year 2003. *Quercus ilex* L. and *Quercus pubescens* Willd. were considered. These species were widely distributed in the city of Rome (Gratani and Crescente 1999; Attorre *et al.*, 2000). We considered ten polluted (P) sites and eight control (C) sites. P and C sites were identified on the basis of the pollution data monitored by Capannesi *et al.* (1981), Gratani and Crescente (1999), Gratani *et al.* (2000). C sites were selected within the Castelporziano Estate (41°45′N, 12°26′E, Rome), characterised by the absence of industrial factories (Capannesi *et al.*, 1980; Gratani and Crescente, 2000).

Microclimate

Atmospheric carbon dioxide concentration (CO_2, ppm) was monitored monthly, using a CO_2 gas analyser EGM-1 (PP Systems, UK), prior to dawn and in the middle of the afternoon at a height of 2 m above the ground at each P and C sites, according to Idso *et al.* (2001).

Air temperatures (T,°C) and relative humidity (RH,%) were measured during the study period using a portable thermohygrometer (HD 8901, Delta Ohm, I).

Related "below-canopy" microclimate (air temperature, T_c, °C, and air humidity RH_c,%) during summer was also analysed with the same instruments to determine the degree to which tree cover influences the climate surrounding people and houses, according to Heisler *et al.* (1994).

Tree structure

Tree structure was analyzed by individual trees of the two selected species (comparable per size): ten trees of each of the two considered species per each P (ten) and C (eight) sites were studied**.** The considered trees were separated into two classes, according to size: small size (tree diameter at breast height, dbh, 20 to 50 cm) and large size (50 to 80 cm); dbh was measured by a wheel.

Plant and crown height (H, m) were measured by a clinometer. The height of the crown was calculated like the difference between the plant height and the insertion's point of the first coppers. The projected crown area (Pc, m^2) was measured by projecting the edges of crown to the ground and measuring the length along one axis from edge to edge through the crown centre. Crown volume (V_c, m^3) was calculated approximating tree crown to geometric solids, according to Karlik and Winer (2001).

Leaf Area Index (LAI) was measured by the "LAI 2000 Plant Canopy Analyzer" (LICOR Inc., Lincoln, USA), and Leaf Area Density (LAD, m^{-1}) was calculated by the ratio of LAI and crown height (Küppers, 2003).

Total photosynthetic leaf surface area (SPT, m^2) was determined multiplying each LAI value by the projected crown area.

Crown damage

The crown damage was determined by the degree of leaves lost considering five indexes of damage: 0: absent; 1: light; 2: moderate; 3: strong; 4: complete, according to Cadahia *et al.* (1991).

CO_2 sequestration

The total yearly CO_2 sequestration capacity was calculated multiplying the photosynthetic rate of each crown (TPCR, μmol CO_2 s^{-1}) by the total photosynthetic activity hours in the year (PTYH, hours). TPCR was obtained multiplying SPT by the mean yearly photosynthetic rate (YPR, μmol CO_2 m^{-2} s^{-1}) per species. YPR and PTYH of each species was calculated using data from Gratani and Crescente (1999) and Gratani *et al.* (2000).

Statistical analysis

All statistical tests were performed using a statistical software (Statistica, Statsoft, USA). The differences of the means were tested by one-way analysis of variance (ANOVA) and Tukey test for multiple comparisons. A multiple regression analysis was calculated to investigate the influence of tree cover on microclimate. The multiple regression was analysed employing T_c as the dependent variable and LAI, LAD, SPT and V_c as independent variables.

Results

Microclimate

Significantly microclimatic difference between P and C sites were measured during the hottest months; air temperature in the city (P sites) during the summer was, on an average, 32 ± 2 °C, 3 °C greater than that of the surrounding zones (C sites) (Table 1).

Air temperature and air humidity at P sites were affected by plant species structure and size: during summer air temperature and relative humidity around *Q. pubescens* monitored plants were on an average 4.5 °C lower and 89% higher, respectively, than those ones monitored around *Q. ilex* plants. Plant structure did not affect significantly air temperature and air humidity at C sites (Table 2).

P sites exhibited higher CO_2 concentration (432 ± 37 ppm, mean value) than C sites (371 ± 8 ppm, mean value) (figure 1).

Tree structure and crown damage

The structural crown traits of the all the considered trees were significantly ($p < 0.001$) different between P and C sites (Table 3). In both P and C sites the mean diameter and height

Table 1 Results of the microclimatic analysis at, polluted (P) and control (C) sites in winter and summer during the study period. Ten P and eight C sites have been considered

	Sites		
Season	*P*	*C*	*p*-level
		T (°C)	
Winter	13.0 ± 1.1	12.4 ± 1.0	N.S
Summer	32.0 ± 2.0	29.0 ± 1.0	<0.01
		RH (%)	
Winter	68.5 ± 7.2	75.5 ± 6	<0.01
Summer	41.0 ± 13.0	45.0 ± 2.0	N.S

T (air temperature), RH (relative air humidity). The mean values are significantly different at $p < 0.01$ (ANOVA). N.S = not significantly different. (number of observation for each site = 240).

Table 2 Microclimatic measurements below the canopy of *Q. ilex* and *Q. pubescens* at, polluted (P) and control (C) sites during the summer 2003. Ten *P* and eight *C* sites have been considered

Sites	*Q. ilex*	*Q. pubescens*	*p*-level
		T_c (°C)	
P	33.9 ± 0.1	29.4 ± 0.3	<0.001
C	28.6 ± 0.5	28.0 ± 0.1	N.S.
		RH_c (%)	
P	27.0 ± 0.4	51.0 ± 5.0	<0.001
C	48.3 ± 0.2	48.5 ± 0.1	N.S.

T_c (air temperature below the canopy), RH_c (relative air humidity below canopy). The mean values are significantly different at $p < 0.001$ (ANOVA). N.S = not significantly different. (number of observation for each site = 120)

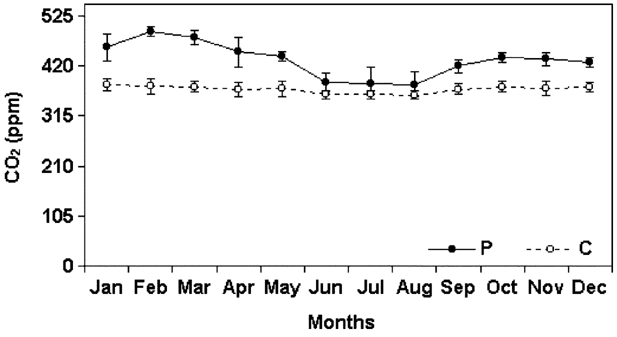

Fig. 1 Monthly trend of CO_2 concentration at polluted (P) and control (C) sites during the study period. Ten P sites and eight C sites have been considred. Each point is the mean of forty measures. Within the same month, means of different sites are significantly different (ANOVA, $p < 0.05$). Standard deviation is shown.

of *Q. ilex* trees was 42.0 ± 4.0 cm and 12.0 ± 1.0 m, respectively for the small class size, and 61.0 ± 1.0 cm and 14.3 ± 0.8 m, respectively, for the large class size.

Q. pubescens mean tree diameter and height were 44.0 ± 1.4 cm and 13.0 ± 1.0 m, respectively, for the small class size, and 62.0 ± 3 cm and 15.0 ± 1.4 m, respectively, for the large class size.

Table 3 Structural tree crown traits of the considered class size at polluted (P) and control (C) sites

	P	C	p
Q. ilex (dbh = 42.0 ± 4.0 cm; H = 12.0 ± 1.0 m)			
n	50	40	
SPT (m^2)	255 ± 10	396 ± 24	<0.001
LAI	3.9 ± 0.2	4.7 ± 0.3	<0.001
LAD (m^{-1})	0.35 ± 0.04	0.48 ± 0.04	<0.001
V_c (m^3)	105 ± 20	149 ± 30	<0.001
Q. ilex (dbh = 61.0 ± 1.0 cm; H = 14.3 ± 0.8 m)			
n	50	40	
SPT (m^2)	475 ± 59	650 ± 28	<0.001
LAI	4.4 ± 0.3	4.9 ± 0.2	<0.01
LAD (m^{-1})	0.47 ± 0.05	0.54 ± 0.04	<0.05
V_c (m^3)	252 ± 19	485 ± 20	<0.001
Q. pubescens (dbh = 44.0 ± 1.4 cm; H = 13.0 ± 1.0 m)			
n	50	40	
SPT (m^2)	510 ± 8	637 ± 10	<0.001
LAI	3.2 ± 0.2	3.6 ± 0.1	<0.001
LAD (m^{-1})	0.32 ± 0.02	0.46 ± 0.03	<0.001
V_c (m^3)	496 ± 25	630 ± 20	<0.001
Q. pubescens (dbh = 62.0 ± 3.0 cm; H = 15.0 ± 1.4 m)			
n	50	40	
SPT (m^2)	661 ± 93	821 ± 67	<0.05
LAI	3.5 ± 0.3	4.1 ± 0.1	<0.01
LAD (m^{-1})	0.34 ± 0.08	0.51 ± 0.07	<0.05
V_c (m^3)	533 ± 52	672 ± 30	<0.001

dbh (diameter at breast height), H (tree height), SPT (total photosynthetic leaf surface), LAI (leaf area index), LAD (leaf area density), V_c (crown volume); n = number of trees for class size. The means values are significantly different at $p < 0.001$ (ANOVA)

LAI values were on an average 10 and 15% lower in P sites than in C sites for the large class size of *Q. ilex* and *Q. pubescens,* respectively (Table 3).

The deciduous species showed a higher SPT in P (661 ± 93 m^2) and C (821 ± 67 m^2) sites than the evergreen one (475 ± 59 m^2, and 650 ± 28 m^2, for P and C sites, respectively) for the large trees (Table 3).

LAD was 50% and 15% higher in *C* sites than in *P* sites for *Q. pubescens* and *Q. ilex*, respectively, and the difference was more evident in the small class size (Table 3).

Q. ilex trees in P sites showed an index of damage of 2 (small class size) and 3 (large class size), and *Q. pubescens* of 1 (small and large class sizes).

CO_2 sequestration

YPR, TPCR, and PTYH calculated for each crown and species, using also data from Gratani and Crescente (1999) and Gratani *et al*. (2000) are shown in Table 4.

Table 4 Diameter at breast height (dbh), tree height (H), mean yearly photosynthetic rate (YPR), total photosynthetic rate of each tree crown (TPCR), total photosynthetic activity hours in the year (PTYH), for the considered species. YPR, TPCR and PTYH was calculated using data from Gratani and Crescente (1999) and Gratani *et al.* (2000)

Species	dbh (cm)	H (m)	Y PR (μmol CO_2 $m^{-2}s^{-1}$)	TPCR (μmol CO_2 s^{-1})	PTYH (hours)
Q. ilex	61.0 ± 1.0	14.3 ± 0.8	6.37 ± 1.80	3026 ± 10	315
Q. pubescens	62.0 ± 3.0	15.0 ± 1.4	10.83 ± 2.00	7159 ± 8	163
Q. ilex	42.0 ± 4.0	12.0 ± 1.0	6.60 ± 0.80	1683 ± 12	315
Q. pubescens	44.0 ± 1.4	13.0 ± 1.0	8.43 ± 1.30	4302 ± 10	163

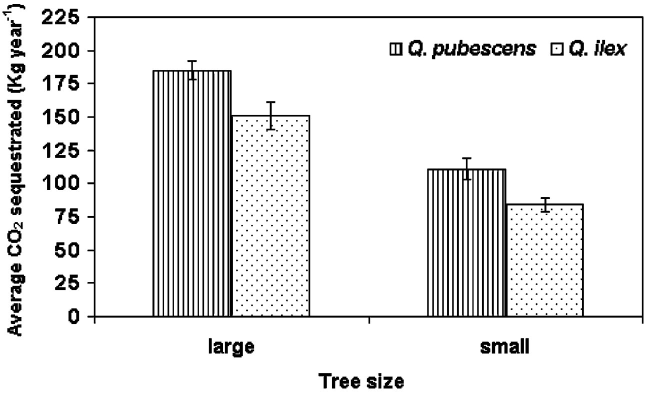

Fig. 2 Average CO_2 sequestrated in the year by individual trees of *Q. ilex* and *Q. pubescens* in relation to their sizes. Large class size (dbh = 61.5 ± 0.7 cm, H = 14.7 ± 0.5 m), small size (dbh = 43.0 ± 1.4 cm, H = 12.5 ± 0.7 m). For each size class and species 50 trees have been considered.

CO_2 sequestration for the large trees class size of *Q. ilex* and *Q. pubescens* was 151 ± 10 and 185 ± 7 Kg year^{-1} of CO_2, respectively.

Trees of small class size had 44 (*Q. ilex*) and 40% (*Q. pubescens*) lower sequestration capacity than large class size trees (figure 2).

Statistical analysis

Multiple regression analysis showed that the crown volume was the significant ($p < 0.01$) variable explaining variation of air temperature below the canopy. Air temperature was negatively correlated with crown volume (i.e. the larger volume had the lower air temperature) (Table 5).

Discussion

Urban areas exhibit climatic differences compared with rural environments due in part to multiple artificial surfaces, high levels of fossil fuel combustion and traffic volume. The urbanisation process in these last years has increased air temperature in Rome; the centre of the city has on an average 1.8 °C higher air temperature and 9% lower air humidity than the control sites. The urban "heat island" intensity may be positively influenced by tree canopy

Table 5 Results of multiple regression analysis using air temperature below the canopy (T_c) as dependent variables and crown volume (V_c), leaf area index (LAI), leaf area density (LAD) and total photosynthetic leaf surface (SPT) as independent variables. V_c and LAD have been the only variable extract by the analisys

Indipendent variable		V_c	LAD
Multiple *R* value	0.65		
Intercept	36.4		
β regression coefficient		−0.76	−0.32
B regression coefficient		−0.008	−5.776
p-level		0.003	0.2

Multiple *R* value, intercept value, unstandardized (*β* coefficient), standardized (B coefficient) regression coefficient and *p*-level of those coefficients are shown.

cover (McPherson *et al.*, 1997); the results show, in fact, that evergreen and deciduous species both contribute to decreasing air temperature in the city, in particular during the hottest months, through shading and transpiration (mean yearly transpiration rates = 2.7 ± 0.2 mol H_2O m^{-2} s^{-1} and 3.7 mol H_2O m^{-2} s^{-1} respectively, data by Gratani and Crescente (1999)). Air temperature around *Q. pubescens* trees is 4.5 °C lower than those measured around *Q. ilex* trees; this is due the larger crown volumes of the deciduous species at P sites (533 ± 52 m^3 for the large class size) compared to trees ones of the same tree size in the evergreen species (252 ± 19 m^3). The shade cast by trees also reduces glare and blocks the diffuse light reflected from the sky to surrounding surfaces, thereby altering the heat exchange between a building and its surroundings (Akbari, 2002). A significant increase in the number of trees in the city could moderate the intensity of the urban "heat island" by altering the heat balance of the entire city.

Moreover, the results show the existence of a strong urban CO_2, dome with a peak CO_2 concentration (on an average 432 ± 37 ppm) at polluted sites, 16% greater than that in the surrounding zones (control sites). The considered evergreen and deciduous tree species both contribute to reducing carbon dioxide concentration. Trees act as a sink for CO_2 by fixing carbon during photosynthesis and storing the excess as biomass (Nowak and Crane 2002). The total carbon sequestration by larger trees (50–80 cm, diameter class) is on an average 151 ± 10 and 185 ± 7 Kg $year^{-1}$ of CO_2 for *Q. ilex* and *Q. pubescens,* respectively. The larger trees of the two considered species tend to extract, on an average, 72% more carbon dioxide from the atmosphere than the smaller trees (20–50 cm, diameter class), and they have a greater total leaf area to trap air borne pollutants (Gratani *et al.*, 2000).

The larger trees of *Q. pubescens* by their greater total photosynthetic leaf surface area (39% higher than that of *Q. ilex*) and their higher yearly mean photosynthetic rate (70% higher than *Q. ilex*), seems to contribute in major role to CO_2 sequestration at P sites. Nevertheless, taking into account leaf longevity (i.e. 12 ± 3 months for *Q. ilex* and 4 ± 2 months for *Q. pubescens,* data by Gratani and Crescente (1999)), *Q. ilex*, by its continuous photosynthetic activity, contributes to reduce CO_2 throughout the year, while the deciduous species contributes to this same reduction only from spring to the beginning of autumn. Thus, the choice of plant species for urban "green" furniture may be set out favouring those species which characterise the natural environment of the urban area, and taking into account the specific capability to improve air quality.

Q. ilex trees show a damage of 2 (small size) and 3 (large size) class in polluted sites while *Q. pubescens* of 1 class (for small and large class sizes); this may be due to the long period of presence (persistence) of *Q. ilex* leaves throughout the year. Nevertheless the functioning capacity of this evergreen species is not compromised by the leaf damage (Gratani *et al.*, 2000).

On the whole, our results suggest that the evergreen and deciduous trees play a major role in sequestering CO_2 and reducing air temperature in the city of Rome, and thereby delaying global warming. Nevertheless, there is a trade—off between greater sequestration by *Q. ilex versus Q. pubescens* by the presence of leaves throughout the year, and also in winter, when the traffic has the highest picks (Gratani and Varone, 2005). Understanding the urban ecosystem dynamics require long-term researches because of the many factors involved (i.e. climate, pollution sources, urbanistic characteristics). Vegetation in the city not only has an ornamental function but also a role in regulating the environmental function: it retains atmospheric water, contributes to evapo—transpiration, represents a filter against pollution and an excellent regulator of the air, heat and damp with the urban surroundings (Hobert *et al.*, 1982). The city of Rome, characterised by the presence of a high volume of the “green”, may represent an ideal system to study the possibility to improving air quality by the selection of species according to their own amelioration capability.

In the last years, the investigators are themselves concentrating on the possibility to develop models that can quantify the role of urban trees in removing CO_2 and pollutants from atmosphere (Nowak, 2000; Brack, 2002). These models need many data on the species composition, age, structure, health, and geographic distribution. Our data concerning tree diameter and height, total photosynthetic leaf surface, crown photosynthetic rates, crown volume, LAI, and LAD, may be used to realise a model helping long-time monitoring and management for the city of Rome. Rome is characterised by the presence of a high volume of the “green” and may represent an ideal system to study the possibility to improving air quality by the use of trees and selection the species by the own capability whose results may be exported in other urban areas.

Acknowledgments The authors thank Mr. N. Gamberini and Miss C. Fagnani for their contributions to the data collection. This paper was supported by the grants CNR 00.00398.ST74.

References

Akbari H (2002) Shade trees reduce building energy use and CO_2 emissions from power plants. Env Poll 116:119–126.

Akbari H, Davis S, Dorsano S, Huang J, Winnett S (1992) Cooling our communites: A guidebook on tree planting and light—colored surfacing. Lawrence—Berkeley Laboratory Report LBL-31587. US EPA Climate Change Division, Washington, DC.

Attorre F, Bruno M, Francesconi F, Valenti R, Bruno F (2000) Landscape changes of Rome through tree-lined roads. Landscape Urban Plann 49:115–128.

Birdsey R (1992) Carbon storage and accumulation in United States forest ecosystems. Gen. Tech. Rep. WO-GTR-59. Radnor, PA: Northeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture; 51 p.

Brack CL (2002) Pollution mitigation and carbon sequestration by an urban forest. Env Poll 116:195–200.

Cadahia D, Cobos JM, Soria S, Clauser F, Gellini R, Grossoni P, Ferreira MC (1991) Observation des dommages sur les essences forestierès méditerranéennes. Commision des Communantés Européennes, Direction Générale de l'Agriculture.

Capannesi G, Gratani L, Amadori M, Bruno F (1980) Livelli di accumulo di 36 elementi in foglie di Quercus ilex nella città di Roma (Italia). Atti del primo congresso Nazionale della S.IT.E., Salsomaggiore Terme (Parma): 21–24 Ottobre 1980, p. 514.

Capannesi G, Gratani L, Amadori M, Bruno F (1981) Le foglie di *Quercus ilex* monitor del grado di inquinamento in area urbana. Notiziario CNEN 3:33–56.

Dwyer JF, McPherson EG, Schroeder HW, Rowntree RA (1992) Assesing the benefits and costs of the urban forest. J Arboric 18:227–234.

Funiciello R, Marra F, Rosa C (1995) I caratteri geologici—stratigrafici. In: Cignini B, Massari G, Pignatti S, (eds) L'Ecosistema Roma. Ambiente e territorio. Fratelli Palombi Editori, Roma, pp. 29–39.

Gratani L, Crescente MF (1999) Indici di valutazione del grado di inquinamento in area urbana. Arch Geob 5:43–50.

Gratani L, Crescente MF (2000) Map—making of plant biomass and leaf area index for management of protected areas. Aliso 19:1–12.

Gratani L, Varone L (2005) Daily and sesonal variation of CO_2 in the city of Rome in relationship with the traffic volume. Atmos Environ (in press).

Gratani L, Pesoli P, Crescente MF (1998) Relationship between photosynthetic activity and chlorophyll content in an isolated Quercus ilex L. tree during the year. Photosynthetica 35:507–516.

Gratani L, Crescente MF, Petruzzi M (2000) Relationship between leaf life—span and photosynthetic activity of *Quercus ilex* in polluted urban areas (Rome). Env Poll 110:19–28.

Gratani L, Crescente MF, Varone L, Blasi C (2003) Trees presence in urban area to improve air quality. Proceedings of the EuroMAB 2002 Meeting, Roma 7–11 ottobre 2002. Accademia Nazionale delle Scienze detta dei XL, Scritti e Documenti 31:101–102

Groffman RM, Pouyat RV, McDonnell MJ, Pickett STA, Zipperer WC (1995) Carbon pools and trace gas fluxes in urban forests. In: Lai R, Kimble J, Levine E, Stewart BA (eds) Soils management and greenhouse effect. Advances in Soil Science. CRC Lewis, Boca Raton, pp. 147–159.

Heisler GM, Grimmond S, Grant RH, Souch C (1994) Investigation of the influence of Chicago's urban forests on wind and air temperature. In: McPherson EG, Nowak DJ, Rowntree RA (eds) Chicago's Urban forest ecosystem: Results of the Chicago Urban Forest Climate Project. General Technical Report No. NE-186, U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Radnor, PA, pp. 19–40.

Horbert M, Blume HP, Elvers H, Sukopp H (1982) Ecological contributions to urban planning. Blackwell, Oxford, pp. 255–275.

Idso CD, Idso SB, Balling RC, Jr. (2001) An intensive two—week study of an urban CO2 dome in Phoenix, Arizona, USA. Atmos Environ 35:995–1000.

Karlik JF, Winer AM (2001) Plant species composition, calculated leaf masses and estimated biogenic emissions of urban landscape types from a field survey in Phoenix, Arizona. Landscape Urban Plann 53:123–134.

Koerner B, Klopatek J (2002) Anthropogenic and natural CO_2 emission sources in an arid urban environment. Env Poll 116:45–51.

Küppers M (2003) Space filling by foliage: The effect of growth form and architecture on the light environment. In: Larcher W (ed), Physiological plant ecology, 4th edn. Springer-Verlag, Berlin, Heidelberg, New York, pp. 40–41.

McPherson EG, Nowak D, Heisler G, Grimmond S, Souch C, Grant R, Rowntree R (1997) Quantifying urban forest structure, function and value: The Chicago urban forest climate project. Urban Ecosystems 1: 49–61.

Moulton RJ, Richards KR (1990) Costs of sequestering carbon through tree planting and forest management in the United States. Gen. Tech. Rep. WO-58. USDA Forest Service, Washington, DC. 46 pp.

Nasrallah HA, Balling RC Jr, Madi SM, Al-Ansari L (2003) Temporal variations in atmospheric CO_2 concentrations in Kuwait city, Kuwait with comparisons to Phoenix, Arizona, USA. Env Poll 121: 301–305.

Nowak DJ (2000) The interactions between urban forests and global climate change. In: Abdollahi KK, Ning ZH, Appeaning A (eds) Global change and urban forest. GCRCC and Franklin Press, Baton Rouge, LA, pp. 31–44.

Nowak DJ, Crane DE (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: Proceedings of the IUFRO Conference. Gen. Tech. Rep. NC-212, St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station, pp. 714–720.

Nowak DJ, Crane DE (2002) Carbon storage and sequestration by urban trees in the USA. Env Poll 116:381–389.

Pal A, Kulshreshtha K, Ahmad KJ, Behl HM (2002) Do leaf surface characters play a role in plant resistance to auto—exhaust pollution? Flora 197:47–55.

Pignatti S (1995) La vegetazione naturale. In: Cignini B, Massari G, Pignatti S (eds) *L'Ecosistema* Roma. Ambiente e Territorio. Fratelli Palombi Editori, Roma, pp. 54–61.

Pearson RL, Wachtel H, Ebi KL (2000) Distance—weighted traffic density in proximity to a home is a risk factor to leukemia and other childhood cancers. J. Air and waste Management Association 50: 175–180.

Sanders RA (1984) Some determinants of urban forest structure. Urban Ecol 8:13–28.

Zapparoli M (1997) Gli insetti di Roma. Considerazioni introduttive ad uno studio di Entomologia urbana. In: Zapparoli M (ed) *Gli insetti di Roma*. Fratelli Palombi Editori, Roma, pp. 21–65.