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Carbon sequestration and noise attenuation provided by hedges in Rome: the contribution of hedge traits in decreasing pollution levels

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ABSTRACT

Hedges are ubiquitous green elements in many European cities. The selection of hedge types characterized by different traits can be suggested for urban greening projects to decrease pollution levels. At this end, carbon dioxide (CO_2) sequestration and noise attenuation capability were analyzed in the following hedge types: *Laurus nobilis*, *Nerium oleander*, *Pittosporum tobira* and *Pyracantha coccinea*, largely used as green infrastructure in Rome (Italy). Representative hedges for each species were selected from high level traffic streets in the city centre (P sites). Traffic density (TD) was monitored simultaneously with CO_2 concentration and noise level (N) in each of the considered P sites. The monthly CO_2 sequestration capability (MSC) was calculated multiplying the total photosynthesis per hedge by the total photosynthetic activity time (in hours) per month. The multiple regression analysis predicted noise attenuation (ΔN) by a linear combination of total leaf area (TLA), total leaf density (TLD) and leaf mass area (LMA) of the considered hedge types. All the considered species, being evergreens, were active all year long, including winter, when CO_2 emissions from road transport peaked. Nevertheless, among the considered hedge types, *P. tobira* and *L. nobilis* were the most efficient species in both MSC (31.6±2.8 and 25.4±2.4 kg CO_2 month^{-1}, respectively) and ΔN (15±1%, mean value). The results give insight on the use of hedges to mitigate pollution effects. Moreover, this method can be used to monitor hedge contribution to air quality, in relation to various elements in the city (i.e. traffic density, new cars produced, application of management projects, local laws). These results might be available for projects based on the use of vegetation in order to improve environmental quality in urban areas.

Keywords: *CO_2 sequestration, evergreen species, hedge, noise attenuation, urban area*

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1. Introduction

Over the past two decades the anthropogenic greenhouse gas emissions have increased contributing to emphasize the effects of global change. A large share of global greenhouse emissions is attributable to cities (Hoornweg et al., 2011) which represent a major source of CO_2 to the atmosphere due to the concentration of human activities that depend on energy from fossil–fuel combustion (Hiller et al., 2011). Cities account for more than 71% of the energy related to global greenhouse gases which is expected to rise up to 76% by 2030 (Hoornweg et al., 2011). Moreover, in urban areas vehicular traffic poses a major impact by emitting combustion gases (Yeh, 2013) and the current urban dynamics, based on continuing trends of sprawl, with a high dependence on private motorized transportation, can significantly contribute to the increase of gas emission rates (Tiwari et al., 2011). Maximum emissions are reported to occur during the daytime with peaks during rush hours (Kordowski and Kuttler, 2010) when the impact of vehicle emissions on CO_2 concentration is indicated by its correlation with traffic levels in several studies (Soegaard and Moller–Jensen, 2003; Gratani and Varone, 2005; Matese et al., 2009). According to Nesamani (2010) the total CO_2 emissions in urban areas due to traffic is 4 575 tons of CO_2 per day and Kakouei et al. (2012) underline for the metropoli-tan area of Tehran, emissions are equal to 26 372, 1 648, 1 433 and 374 tons of CO_2 per day for private cars, motorcycles, buses, and taxis, respectively.

Vegetation covers comparatively large segments of urban areas (i.e. private and public gardens, parks, sport fields, hedges and tree–lined avenues) and it may potentially slow CO_2 atmospheric concentration by fixing carbon during photosynthesis and storing the excess as biomass in plant tissues at different rates (Nowak and Crane, 2002; Gratani and Varone, 2006; Liu and Li, 2012).

After air pollution, noise pollution reduces the quality of the urban environment (Yang et al., 2010) because it affects human health unfavorably, both physically and psychologically (Stansfeld and Matheson, 2003; Maleki et al., 2010). Noise pollution in cities is generated through different sources, such as road traffic, construction and commercial activities, industries and airports (Maleki et al., 2010). Human hearing is more sensitive to low and medium frequencies of the waves produced by traffic (Ouis, 2001). In the European Union about 80 million people suffer from unacceptable noise levels (above 65 dB), while an additional 170 million people are exposed to noise levels between 55 and 65 dB (Yang et al., 2010). Transportation systems, including roads, railways and air traffic characterize the modern urban environment (Onder and Kocbeker, 2012) and in recent years, road traffic has played a dominant role in causing environmental noise (Onder and Kocbeker, 2012).

Studies considering noise reduction with plants in urban areas is of great importance (Fang and Ling, 2003; Fang and Ling, 2005; Maleki et al., 2010). Many studies have been conducted to reduce noise levels and their negative effects in various countries all over the world (Zannin et al., 2002; Maleki et al., 2010). Nevertheless, few data have been reported on the role of plants traits on noise reduction (Fang and Ling, 2003).

Among urban green elements, groups of natural or planted shrubs (hedges) are ubiquitous elements of many public, commercial and residential landscapes (Kendal et al., 2008). Nevertheless, there are few quantitative recommendations regarding principles for hedge planting designs to reduce noise pollution (Reethof and Heisler, 1976; Pandya, 2001; Fang and Ling, 2005; Martinez–Sala et al., 2006). Urban vegetation can better contribute to reduce outdoor noise from road traffic, in comparison to plastic or other such man–made material barriers (Kragh, 1979; Fang and Ling, 2005; Yang et al., 2011). The mechanism of noise attenuation in plants is due to the capacity of leaves to absorb acoustic energy by transferring the kinetic energy which vibrates air molecules in a sound field to the vibration pattern of the leaves (Herrington, 1976; Yang and Gan, 2001; Maleki et al., 2010; Pathak et al., 2011). In this way, vibration energy is withdrawn from the acoustic field and a part of it is lost by transferring to heat since leaf friction occurs in a vibrating plant (Aparicio–Ramon et al., 1993; Lercher, 1996). Species diversity of the noise–reducing spectrum may be a potential factor that can be a buffer against certain frequencies, particularly the middle and low frequencies created by traffic (Yang et al., 2010). In European cities built–up areas have been increased by 20% from 1980 to 2000 (EEA, 2002). As cities grow and become more densely settled, increasing impervious land cover replaces trees and indigenous vegetation (Millward and Sabir, 2011). Thus, cities play a critical role in maintaining ecological, economic and social being (Nagendra and Gopal, 2011; Yang et al., 2011). Efforts to promote urban greening require more than knowledge of the green urban environment general benefits (Attwell, 2000; Millward and Sabir, 2011) and urban policies dealing with green area management and implementation should be stressed. At a local level, Authorities should efficiently manage green areas in the city in order to maintain their productivity to secure a better quality of life (Torres and Pinho, 2011). Moreover, green spaces in cities are associated with the increase in property values, perceived consumer friendliness and sense of well–being (Payton et al., 2008).

The main objective of the present research was to characterize structural traits of the hedge types traditionally used for green infrastructure in Rome (Italy) in order to quantify their CO_2 sequestration and noise attenuation capability, in consideration of the high traffic levels in the city centre. The collected data could be used for an urban inventory available for urban green projects to improve environmental quality by the selection of species according to their own amelioration capability.

2. Methods

2.1. Sites and species description

The study was carried out in the city of Rome in the period January–July 2011 in order to analyze variations in CO_2 concentration and noise level in relation to traffic density. The most representative species traditionally used for hedges in Rome [*Laurus nobilis* L, *Nerium oleander* L*, Pittosporum tobira* (Thunb.) Aiton, and *Pyracantha coccinea* M. Roem.] were analyzed. *Laurus nobilis* is an evergreen species native to the southern Mediterranean region, characterized by sclerophyllous leaves (Conforti et al., 2006) which adapts to semi–arid conditions and coastal environments (Rhizopoulou and Mitrakos, 1990). *Nerium oleander* L. is an evergreen shrub species native to the Mediterranean region (Rentzou and Psaras, 2008) and used as an ornamental species in gardening, yards and street medians (Delaney, 2008). *Pittosporum tobira* (Thunb.) Aiton is an evergreen shrub species native of China and Japan, cultivated in many geographical areas as an ornamental species for its attractive foliage and showy, sweet–scented flowers (Zhou et al., 2004). *Pyracantha coccinea* M. Roem. is an evergreen shrub species native to South–East Europe and Asia, which produces fruits profusely and is widely used in gardens, making it a widely available resource for frugivorous birds (de Villalobos et al., 2010).

The considered hedge types were selected in four representtative high traffic streets (P sites: P_1, P_2, P_3, and P_4) inside the city centre (Figure 1). In particular, *L. nobilis* was selected along the Tiburtina Street (P_1, 41°53’51’’N; 12°30’46’’E, specifically, along the track from Tiburtina Square to Verano Square, *P. tobira* along the Circonvallazione Gianicolense Street (P_2, 41°52’22”N; 12°27’48”E), *P. coccinea* along the Enrico De Nicola Street (P_3, 41°54’10’’N; 12°29’59’’E) and *N. oleander* along the Muro Torto Street (P_4, 41°54’43’’N; 12°28’51’’E). During the study period, the considered hedges were not subjected to pruning practices. All the selected hedges had a mean height of 1.50±0.5 meter.

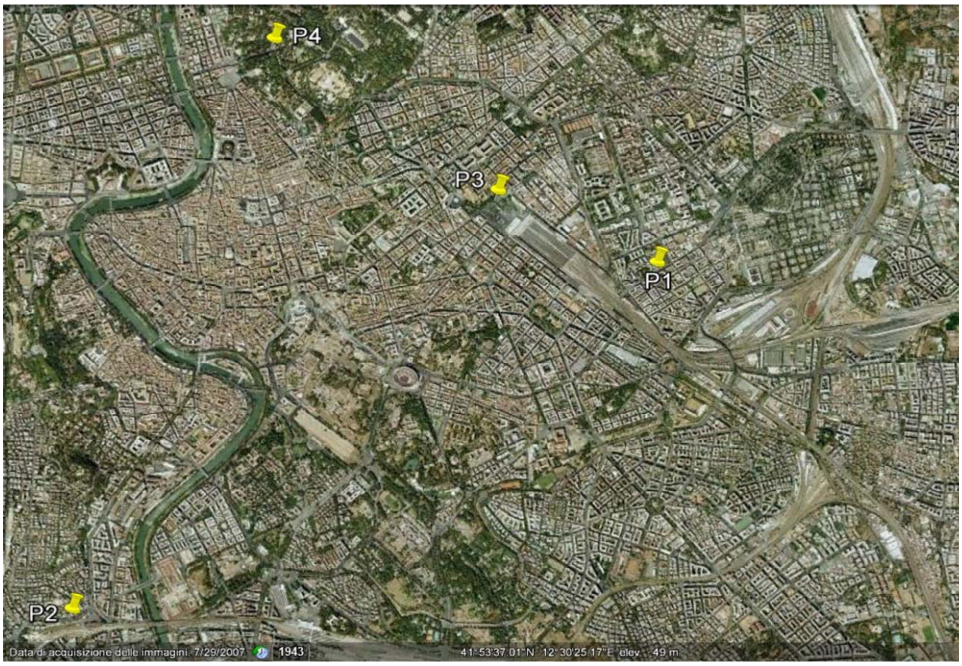

Figure 1. *Map of the considered P sites (high traffic streets) within the city centre in Rome where the considered hedges were sampled.* $\boldsymbol{P_1}$*=Tiburtina Street,* $\boldsymbol{P_2}$*=Circonvallazione Gianicolense,* $\boldsymbol{P_3}$*=Enrico De Nicola Street,* $\boldsymbol{P_4}$*=Muro Torto Street.*

In each of the considered P sites, structural hedge traits and morphological leaf traits were analyzed along a representative track (25 m long) for each hedge type, at 1.00 meter from the soil level. Net photosynthesis, traffic density, CO_2 concentration and noise levels were measured in the considered P sites during the study period.

2.2. Climate

Rome had a Mediterranean type of climate. The average total yearly rainfall is 694 mm. The average minimum air temperature of the coldest month (January) is 5.2±1.7 °C, and the average maximum air temperature of the hottest month (July) is 31.0±1.0 °C. Most of the total rainfall is distributed in autumn, and drought period is from June to August (Data provided by the Meteorological Station of the Collegio Romano, for the period 1995–2010). During the study period (January–July 2011), $T_{\min}$ of the coldest month (February) was 4.2±1.5 °C and $T_{\max}$ of the hottest month (July) was 28.8±1.4 °C. Total rainfall of the study period was 384 mm.

2.3. Morphological leaf traits

Measurements of leaf morphological traits of the species forming the considered hedge types were carried out in June when leaves were fully expanded (n=40 sun leaves per hedge type), according to Fang and Ling (2003). The following parameters were measured: projected leaf surface area (excluding petiole) (*LA*, cm^2), obtained by the Image Analysis System (Delta–T Devices, UK), and leaf dry mass (*DM*, mg), determined drying at 80 °C to constant mass. Leaf mass per unit of leaf area (*LMA*, mg cm^{-2}) was calculated by the ratio of DM and *LA* (Larcher, 2003).

2.4. Structural hedge traits

Total leaf surface area (*TLA*, m^2) was calculated multiplying the total number of leaves by the average *LA*. The total number of leaves was counted in ten sections (each of one m^2) distributed along the considered hedge track per each hedge type.

Total leaf density (*TLD*, g m^{-3}) of the considered hedge types was calculated as the ratio between total leaf biomass per hedge and the volume of the hedge (m^3), according to Henry et al. (2009). Total leaf biomass per hedge was calculated multiplying the total number of leaves per hedge by the average DM. The volume of the hedge was calculated by assigning a simple geometric solid to the hedge form, according to Karlik and Winer (2001).

2.5. CO_2 concentration and traffic density

Atmospheric carbon dioxide concentration (CO_2, ppm) was monitored at P sites (P_1, P_2, P_3, P_4) using a CO_2 gas analyzer EGM–1 (PP Systems, UK). Measurements were carried out at 1 m from the soil level, at a distance of 2 m from the source of the noise (traffic), from 8:00 to 11:00 a.m. (peak hours, Gratani and Varone, 2005), in three following sampling days per month with the same weather conditions, during the study period. Traffic density (*TD*, cars min^{-1}) was monitored in the same time of CO_2 concentration measurements in each of the considered P sites.

2.6. Noise level measurements

Noise level (*N*, dB) was monitored simultaneously with *TD* and CO_2 measurements, in each of the considered P sites (P_1, P_2, P_3, P_4) using two portable sound level meters with the same technical characteristics (Testo 816, class 2, Italy) under the same weather conditions to eliminate the effect of climate on the results, according to Fang and Ling (2003) and Embleton (1963). Measurements were carried out at 1 m from the soil level and at a distance of 2 m from the source of the noise (traffic), at the same time, on the side of the hedge exposed to the street (N_{ext}) and on the corresponding interior side of the hedge (N_{int}), according to Fang and Ling (2003) and the relative noise attenuation (ΔN, %) was calculated as $(N_{ext}-N_{int})/N_{ext}$)x100.

Embleton (1963) ascertained that the molecular absorption was slight and the effects due to climate negligible when weather conditions were similar. Thus, measurements were carried out under the same weather conditions at a wind velocity of less than 2 m s^{-1}, during sunny days, according to Cook and Van Haverbeke (1974) and Fang and Ling (2003).

2.7. Net photosynthesis measurement and CO_2 sequestration capacity of hedge

Measurement of net photosynthesis (P_N, µmol CO_2 m^{-2} s^{-1}) was carried out using an infrared gas analyzer (ADC LC*pro*+, UK), equipped with a leaf chamber (PLC, Parkinson Leaf Chamber). Measurements were made on fully expanded sun leaves (four leaves per hedge, per each sampling day), under natural conditions, on cloud – free days (PAR≥1 200 µmol photons m^{-2} s^{-1}, saturating level). Measurements were carried out during the day from 07:30 to 16:30 to ensure that near maximum daily photosynthetic rates were measured (Reich et al., 1995). The P_N values shown represented the mean of the maximum values calculated in three days measurements per month. The total photosynthesis per hedge (*TP*, µmol CO_2 m^{-2} s^{-1}) was calculated by multiplying *TLA* by the mean maximum P_N rates for each sampling occasion, according to Gratani and Varone (2006). The monthly CO_2 sequestration (*MSC*, µmol CO_2 $month^{-1}$) per each hedge type was calculated multiplying *TP* by the total photosynthetic activity time (in hours) per month, according to Gratani and Varone (2006). The yearly CO_2 sequestration per each hedge type was also calculated.

2.8. Statistical analysis

Differences of the means were tested by a one–way analysis of variance (ANOVA), and Tukey test for multiple comparisons. Simple regression analysis was carried out to evaluate the relationship between CO_2 concentration and *TD*, and between noise level and *TD*. Moreover, a multiple regression analysis was carried out using ΔN as dependent variable, and *TLA*, *TLD* and *LMA* as independent variables, in order to evaluate the relative contribution of the structural hedge traits to noise attenuation.

3. Results

3.1. Structural hedge traits and morphological leaf traits

TLD varied from 788±104 g m^{-3} (*P. coccinea*) to 1 267±200 g m^{-3} (*L. nobilis*). *TLA* was the highest in *L. nobilis* (152±9 m^2) and the lowest (42±3 m^2) in *P. coccinea* (Table 1).

Morphological leaf traits were significantly different for the considered hedge types (Table 1). *LA* was the highest in *N. oleander* (28.4±1.0 cm^2), followed by *P. tobira* (17.8±1.2 cm^2), *L. nobilis* (17.3±0.8 cm^2) and *P. coccinea* (6.7±0.4 cm^2). *LMA* was the highest in *N. oleander* (16.4±0.7 mg cm^{-2}) and the lowest in *P. coccinea* (8.8±0.2 mg cm^{-2}).

3.2. CO_2 concentration and traffic density

The seasonal CO_2 trend in P sites showed the highest concentrations from January to April (628±8 ppm, mean value of the P sites) decreasing, on average, by 12% in May and June (mean value) and by 25% in July (Figure 2A). Traffic density peaked from January to April (42.1±10.8 cars min^{-1}, mean values of the P sites) decreasing by 11% in May and June and by 25% in July (Figure 2B).

Table 1. *Structural hedge traits and morphological leaf traits of the considered hedges*

Species	TLA (m^2)	TLD ($g\ m^{-3}$)	LA (cm^2)	LMA ($mg\ cm^{-2}$)
N. oleander	74±13a	795±97a	28.4±1.0a	16.4±0.7a
L. nobilis	152±9b	1 267±200b	17.3±0.8b	10.4±0.2b
P. tobira	145±23b	1 008±160c	17.8±1.2b	12.8±0.2c
P. coccinea	42±3c	788±104a	6.7±0.4c	8.8±0.2d

TLA=Total leaf area, TLD=total leaf density, LA=leaf area, LMA=leaf mass area. Mean values (±S.E.) are shown.
For each trait the mean values followed by different letters indicate significant differences (p ≤ 0.05) among the species.

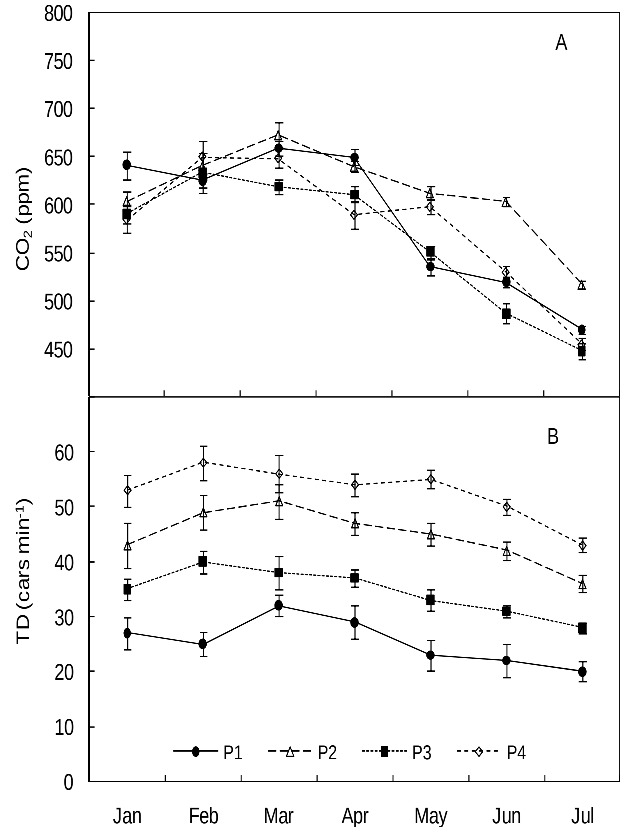

Figure 2. *Trend of* ***(A)*** *atmospheric carbon dioxide (CO_2) concentration and* ***(B)*** *traffic density (TD) during the study period at the considered P sites. Mean values (±S.E.) are shown. P_1=Tiburtina Street, P_2=Circonvallazione Gianicolense, P_3=Enrico De Nicola Street, P_4=Muro Torto Street.*

3.3. Noise measurements

At the P sites, the considered hedges were characterized by a significantly ($p \leq 0.05$) difference in ΔN (Figure 3). ΔN was higher in *P. tobira* and *L. nobilis* (15 and 14%, respectively) than in *P. coccinea* and *N. oleander* (11% and 8%, respectively).

3.4. Net photosynthesis and CO_2 sequestration

P. coccinea had the highest P_N (14.8±0.8 μmol CO_2 m^{-2} s^{-1}, mean value of the study period) than the other species (Figure 4). In all the considered hedge types, the highest P_N rates were measured in May decreasing, on an average, by 37% in July.

Among the considered species, *P. tobira* and *L. nobilis* had the highest *MCS* (31.6±2.8 and 25.4±2.4 Kg CO_2 $month^{-1}$, respectively), followed by *N. oleander* (17.3±2.4 Kg CO_2 $month^{-1}$) and *P.-coccinea* (11.8±0.6 Kg CO_2 $month^{-1}$). The total yearly sequestration capacity was 142, 208, 305 and 379, kg CO_2 y^{-1} in *P. coccinea*, *N. oleander*, *L. nobilis* and *P. tobira*, respectively.

3.5. Statistical analysis

The simple linear regression analysis explained the relationship between CO_2 and *TD*, and between *N* and *TD* (Table 2); moreover, the multiple regression analysis showed that 82% of ΔN variations was due to a combination of *TLA*, *TLD* and *LMA*, according to the following equation: $y=18.098+(0.0794\ x_1)-(0.00690\ x_2)-(0.611\ x_3)$ where *y* was the dependent variable (i.e. ΔN) and x_1, x_2 and x_3 were the independent variables ($x_1=TLA$; $x_2=TLD$; $x_3=LMA$).

Table 2*. Simple regression analysis*

y–x	Equation	R^2
CO_2–*TD*	y=493.391+2.327x	0.16
N–*TD*	y=65.902+0.141x	0.33

CO_2=Atmospheric CO_2 concentration, TD=traffic density N=noise level. The regression equation and determination coefficient (R^2) are shown. The regressions were significant at $p \leq 0.05$.

The standardized β coefficient was 1.1809, –0.4916 and –0.5767 for *TLA*, *TLD* and *LMA*, respectively. In particular, *TLA* and *LMA* were the most significant variables ($p<0.001$) which explained ΔN variations (Table 3).

4. Discussion

Urbanization which is characterized by a high human population density and development of commercial and industrial infrastructure has a variety of effects on the local environment (Loram et al., 2008). In such context, any amelioration of the physical environmental conditions may have an important impact upon the population. Urban greening can generate significant ecosystem services, such as offsetting carbon emission, removing air pollution, reducing noise and offering recreation (Jim and Chen, 2009). Deeper comprehension of urban ecosystem services could provide plausible information for cost–benefit–analysis on related projects (Jim and Chen, 2009). Nevertheless, understanding urban ecosystem dynamics requires long–term research because of many factors (i.e. climate, pollution sources, urban characteristics) are involved (Gratani and Varone, 2006). In order to achieve this, it is necessary to survey data on species presence, distribution, size, and on their potential role in air quality amelioration. The European Council gives the fundamental provisions on vehicle safety and CO_2 and noise emissions from road transport. In particular, with regard to noise legislation, the EU has adopted the Directive 2002/49/EC which deals with reducing noise emitted by major sources, specifically road and rail vehicles. Noise pollution affects so many populations, thus the research on noise control is plentiful. Urban greening may play a notable role in environmental conditions and improvement of public life (Skarback, 2007). Plants have often been proposed as a natural way to reduce noise levels, but the effectiveness of species and traits are still being debated. It has been hypothesized that certain types of vegetation and leaf traits may affect the foliage's ability to achieve noise attenuation (Yang et al., 2010).

Table 3. *Results of the multiple regression analysis carried out using ΔN as dependent variable and TLA, TLD and LMA as independent variables. Multiple R value, intercept value, regression coefficients, standardized β coefficient and significance levels (p–level) are shown*

Independent variable		TLA	TLD	LMA
Multiple *R* value	0.823			
Intercept	18.098			
Coefficient		0.0794	–0.0069	–0.611
Coefficient β		1.1809	–0.4916	–0.5767
p–level		<0.001	<0.05	<0.001

ΔN=relative noise attenuation; TLA=total leaf surface area; TLD=total leaf density
LMA=leaf mass area

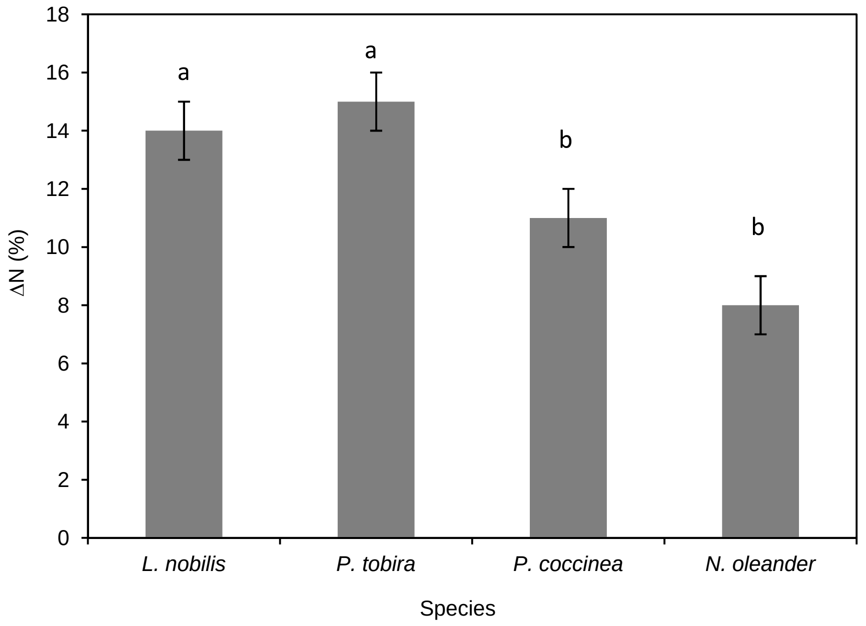

Figure 3. *Relative noise attenuation (ΔN) of the considered hedges during the study period. Mean values (±S.E.) are shown. Mean values with different letters significantly differ (p≤0.05).*

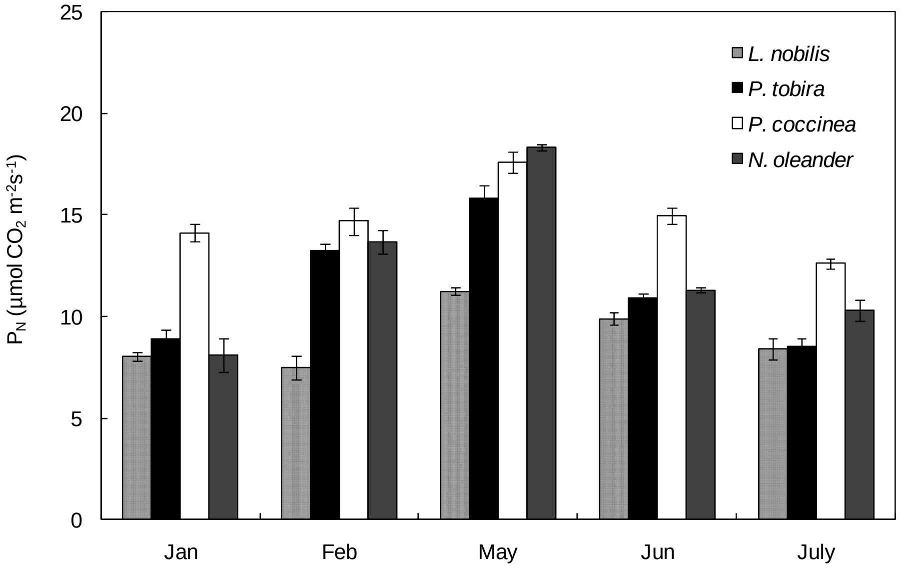

Figure 4. *Trend of net photosynthesis (P_N) monitored on the considered hedges during the study period. Mean values (±S.E.) are shown.*

In 2006, the city of Rome ratified on a local level the Aalborg Commitments, established during the Aalborg+10 Conference in 2004, that deals in promoting the sustainability of European cities through the involvement of the local government to implement strategies concerning the decrease of greenhouse gas emissions and transport activity. The urbanization process in Rome has been increasing in recent years, and many new suburban areas have been built by scaling down free areas surrounding the city (129 000 ha of urbanized area, 2 810 931 inhabitants of which 32 569 live in the city centre). The territory is subdivided into agricultural areas (48%), built up areas (37%), and green areas (15%) (Gratani and Varone, 2006). The urban traffic in Rome is principally made up by private cars (76%) and motorcycles (16%) (ACI, 2010). The public transport system is composed of 2 287 means that serves a vast territorial area of the city (1 285 km^2) and a total number of transported passengers of 1 132 per minute (ATAC, 2011). Nevertheless, Rome has a large volume of green areas, constituted by strips of persistent meadows in suburban areas, trampled down environments, fragments of deciduous and evergreen woods and different shrub types (Gratani and Varone, 2006). A large part of the urban green areas is covered by historical residences with large parks where many tree and shrub species indigenous to the Mediterranean landscape. Hedges have been used in Rome since the 15th century on the grounds of historical residences and, since the beginning of the 20th century, to mark the boundary of gardens and tramways along roads and railways. At the present time, a majority of the avenues, parks, small gardens and flower–beds in Rome are bordered by hedges that on the whole constitute an important portion (7–10%) of the urban greening. Moreover, the on–going urbanization of Rome makes it an example of a mega–city where air pollution will continue to increase causing risks to the health of the population.

Our results on the whole underline that the considered hedges have a different CO_2 sequestration and noise attenuation capability as related to the species and hedge leaf traits, becoming important elements in urban greening**.** Shrubs reduce noise by their dense foliage and branches (Fang and Ling, 2003). In particular, *P. tobira*, *P. coccinea* and *L. nobilis,* which are characterized by ovate or elliptic leaf shapes, are more efficient in noise attenuation (ΔN=13±2%, mean value) than *N. oleander* characterized by a narrow leaf shape (ΔN=8±1%). Moreover, ΔN is related to hedge traits specifically in *TLA*, *TLD* and *LMA*, as underlined by the results of the multiple regression analysis. Among these traits, *LMA* has the largest β – coefficient value showing that it may have an efficient role in noise attenuation. In fact, comparing the species characterized by the same leaf shape: *P. tobira* and *L. nobilis* have a higher *LMA* (11.6±1.7 mg cm^{-2}, mean value) than *P. coccinea* (8.8±0.2 mg cm^{-2}) which determines a 36% higher ΔN. According to Yang et al. (2010), a higher *LMA* is due to a higher leaf mass, thus more energy can be lost during the sound wave propagation through the hedge which causes larger noise attenuation.

Moreover, the regression analysis underlines the role of *TLA* in reducing noise. In fact a higher *TLA* (i.e. a larger total surface area covered by leaves) offers a greater surface area contacting the sound front advance, according to the results of Yang et al. (2010). A greater surface area provides a large sound diffusion and absorption (Cook and Van Haverbeke, 1974). Aylor (1972) underlines that foliage reduces sound transmission especially at higher frequencies where scattering is enhanced with the increase in leaf width and weight. Diffusion prevails over absorption to reduce the acoustic energy (Cook and Van Haverbeke, 1974).

The relationship between leaf density and noise attenuation is not always clear in current literature (Fabbri and Della Valle, 2010), because there are natural compensative factors such as number and size of branches that can affect hedge density in noise attenuation by their role in noise scattering (Fabbri and Della Valle, 2010). In fact, the results of the multiple regression analysis give the lowest β – coefficient value for *TLD*, which is negatively but not significantly (p=0.049) correlated with ΔN.

As concerns CO_2, its flux has been quantified in a limited number of cities around the world (Ramamurthy and Pardyjak, 2011); such studies have focused on anthropogenic CO_2 emissions from fossil fuel burning and not the role of vegetation. Plants contribute differently to reduce carbon dioxide concentration by sequestration, depending on plant traits, in particular, *habitus* (evergreen and deciduous species), structure (trees, shrubs, hedges) and size. With regard to plant size, Gratani and Varone (2006) show that larger trees have a total carbon sequestration 67%–80% higher than smaller trees. Compared to tree species, the considered hedges have a lower CO_2 sequestration capacity (on an average 77% lower). Nevertheless, considering the large quantity of hedges in the city centre, where there is heavy traffic all day long, their total CO_2 sequestration contribution plays an important role in the amelioration of air quality. In congested areas people are concerned both with loudness and limited space, thus it seems logical to employ hedges to reduce CO_2 and noise pollution, according to the results of Aylor (1972). Moreover, according to Fang and Ling (2003), the use of hedges planted under trees in the high traffic avenues of a city seems to be the best solution to decrease noise and CO_2 concentration. Plant species should be selected considering pollution reduction effects in addition to their ecological and aesthetical features (Booth, 1991) and all their characteristics which are suitable for the specific environmental conditions (Maleki et al., 2010).

Moreover, the results show significant CO_2 concentration variation during the study period at the considered P sites with a peak from January to April in relation to the largest traffic density (42.1±10.8 cars min^{-1}, mean value) and a decrease by 25% in July. Gratani and Varone (2005) show 18% higher CO_2 concentration in the city centre than in the surrounding zones, underlining the importance of trees and shrubs to sequester CO_2, thus reducing the concentration in urban areas. *MCS* varies significantly in the considered hedge types, and the total yearly CO_2 sequestration is the highest in *P. Tobira* and *L. nobilis*.

In recent years, researchers are concentrating on developing models that can quantify the role of urban vegetation in removing pollutants from the atmosphere (Nowak and Crane, 2000; Brack, 2002). Ecologists, planners, designers and the public are increasingly concerned about how these changes influence daily life and affect the sustainability of quality of life for future generations (McPherson et al., 2011). Considering the expansion of urban areas around the world, much data are necessary in order to have useful models. Our results on the whole underline that all the considered hedge types may improve the quality of the urbanized area by having a role in CO_2 sequestration and noise attenuation. Moreover, it is important to consider that the hedges under study, being evergreen, are active also in winter when traffic peaks. Among the considered hedge types, *L. nobilis* and *P. tobira* are the most efficient in both carbon dioxide sequestration and noise attenuation capability, considering also that they have a greater tolerance to severe pruning and a large ability to maintain high shoot density and basal foliage.

There has been little research on preference for different kinds of hedges, and most texts recommend that native plant material should be used (Hitchmough, 1994). However, the preservation of biodiversity has become an important driver in many contemporary landscapes (Kendal et al., 2008). Thus, we have selected the most historically used hedges which are well adapted to the climate of Rome. The results give insights to the use of selected hedges in order to mitigate pollution effects and improve the urban sustainability. Moreover, the selected method allows the monitoring of polluted urban areas in evaluating hedge contribution to air quality, according to variations in city elements (i.e. traffic density, new cars produced, application of management projects, local laws).

The city of Rome may represent an ideal system to study the possibility of improving air quality by the selection of specific species and the results may be extrapolated to other urban areas. Our data concerning leaf density and consistency, CO_2 sequestration, and noise attenuation capability of the considered hedges could be incorporated in a geographic information system available for urban greening projects.

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