Ecological Services of Urban Forest in Barcelona

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Universitat Autònoma de Barcelona

Bellaterra

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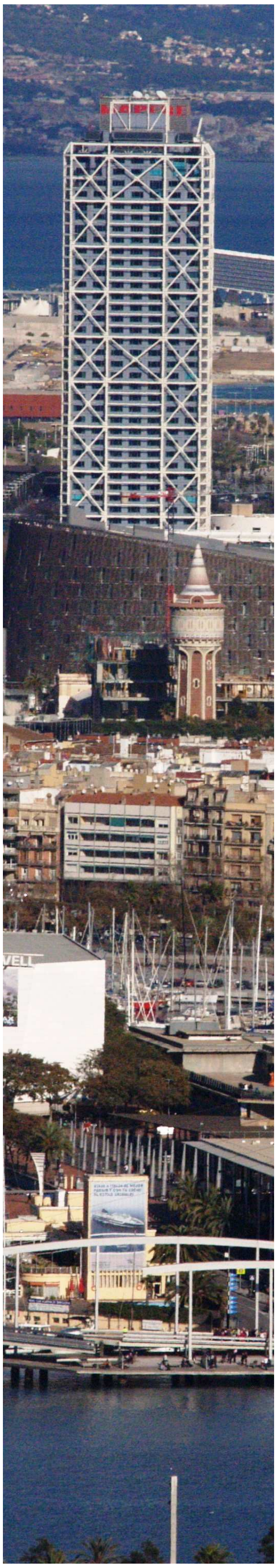


Forests and urban trees generally offer multiple services and environmental benefits to society. These trees are distributed into different land uses (in our case, land uses are defined from the third edition of Mapa Ecològic de Barcelona, 2006), ranging from forest environments and gardens, to densely built areas or polluted urban environments. The structure, and consequently the composition, of urban forest vary in these different land uses, whether public or private. Trees, and the functions and services that they offer, such as air quality improvement, carbon sequestration or temperature reduction, are directly influenced by management and actions that affect its structure (composition of species, number and location of individuals...). Therefore, proper management of urban green spaces may increase the environmental benefits of trees present in our city. The first step to improve the management of urban forest is to evaluate their current structure and benefits.

On January 2009, began a study to quantify the effects of urban forest from different plots distributed throughout the entire city of Barcelona (including the areas of Montjuïc and Collserola), going from the most natural to the most urbanized zones. This assessment was mainly analyzed with the UFORE model (Urban Forest Effects), a computer program able to evaluate the structure of urban forest, like the species composition, tree density and numerous derived functions, such as storage and carbon sequestration, pollution reduction, volatile organic compounds formation, as well as other important services.

The following summarizes the results of this report, which mainly involve the analysis of UFORE's model for the city of Barcelona. The report describes the structure of urban forest and the ecological benefits derived from this urban forest (shrubs and trees) of the city. Other environmental services such as noise pollution, water cycle and vulnerability of urban forest to the climate change, will be also treated.

Executive Summary of UFORE's results:

Land use -hectare (ha)-: The total area studied has an extension of 10,121ha and it has been analyzed with 579 plots distributed into the following land uses:

Urban forest:	806 ha	(7.96%)	50 plots
Natural forest:	2,184 ha	(21.6%)	125 plots
Residential (1-2 family):	424 ha	(4.19%)	20 plots
Multifamily residential:	3,666 ha	(36.2%)	204 plots
Transport:	513 ha	(5.07%)	30 plots
Institutional:	776 ha	(7.67%)	39 plots
Commercial/Industrial:	1,185 ha	(11.7%)	70 plots
Intensive used areas without building:	567 ha	(5.60%)	41 plots
Total	10,121 ha		579 plots

Tree cover by land use:

Urban forest:	56.30%	Transport:	17.50%
Natural forest:	49.50%	Institutional:	4.60%
Residential:	43.10%	Commercial/Industrial:	1.80%
Multifamily residential:	15.20%	Intensive used area:	25.30%
Total	**25.20%**		

Shrub cover by land use:

Urban forest:	6.5%	Transport:	3.2%
Natural forest:	26%	Institutional:	0%
Residential:	9%	Commercial/Industrial:	0%
Multifamily residential:	1.9%	Intensive used area:	0.9%
Total	**7.3%**		

Estimated number of trees by land use:

Urban forest:	212,437	(14.9%)	Transport:	28,214	(2%)
Natural forest:	799,452	(56.3%)	Institutional:	14,381	(1%)
Residential:	86,809	(6.1%)	Commercial/Industrial:	5,856	(0.4%)
Multifamily residential:	223,304	(15.7%)	Intensive used area:	49,370	(3.4%)

Total **1,419,823 trees** (14 % of those are street trees)

Land cover of Barcelona:

Impervious soil	Buildings:	3,138 ha	31%
	Cement, tar and rocks:	3,340 ha	33%
Previous soil	Soil, herbs, grass and water:	3,644 ha	36%

Most common trees in the entire urban area (including Montjuïc and Collserola):

Quercus ilex:	313,372	(22.1% of the entire population)
Pinus halepensis:	290,525	(20.5% of the entire population)
Platanus x acerifolia:	93,212	(6.6% of the entire population)
Pinus pinea:	69,749	(4.9% of the entire population)

Most common trees inside the city of Barcelona:

Platanus x acerifolia:	18,744	(8.8% of the urban forest population)
Cupressus macrocarpa:	15,620	(7.4% of the urban forest population)
Ligustrum lucidum:	13,668	(6.4% of the urban forest population)
Celtis australis:	11,715	(5.5% of the urban forest population)

Tree population by diameter class (DBH=stem diameter at 1.3 meters)

2.5 - 7.6 cm:	13.5%	30.6 - 38.1 cm:	6.3%
7.7 - 15.2 cm:	34.5%	38.2 - 45.7 cm:	3.7%
15.3 - 22.9 cm:	22.6%	45.8 - 53.3 cm:	1.7%
23.0 - 30.5 cm:	15.5%	53.4 - + cm:	2.0%

Trees and air pollution removal:

The urban forest influences the air pollution by removing atmospheric pollutants, such as ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO) and particulate matter less than 10 microns (PM10). Ufore has estimated than trees and shrubs of Barcelona have removed 305.6 tons of pollutants from the air during 2008. The associated value of this ecological service is more than a million of Euros.

Air pollution removal and its estimated value to society (2008):

Carbon monoxide (CO):	5.6 tons	3,693 €
Nitrogen dioxide (NO_2):	54.6 tons	253,290 €
Ozone (O_3):	72.6 tons	336,941 €
Particulate mater (PM10):	166 tons	514,280 €
Sulfur dioxide (SO_2):	6.8 tons	7,703 €
Total	**305.6 tons**	**1,115,908 €**

Trees and Biogenic VOC Emissions:

Volatile organic compounds (VOC) can contribute to ozone (O_3) and carbon monoxide (CO) formation. The amount of VOC emissions depends on the species, leaves biomass, air temperature and other environmental factors. In 2008, trees and shrubs in Barcelona emitted 183,979 kg of VOC, 31,966 kg of CO and 304,468 kg of O_3.

Total annual emissions of VOC, net CO (formed - removed) and net O_3 (formed - removed) by land use for trees and shrubs in Barcelona (2008):

	VOC emissions (kg)	Net CO (kg)	Net O_3 (kg)
Urban forest:	31,365	5,527	54,295
Natural forest:	87,313	15,086	126,017
Residential:	14,810	2,644	28,440
Multifamily residential:	28,179	4,691	50,725
Transport:	6,006	1,049	12,858
Institutional:	4,776	898	4,751
Commercial/Industrial:	1,294	229	3,401
Intensive used areas without building:	10,236	1,842	23,981
Total	**183,979 kg**	**31,966 kg**	**304,468 kg**

Trees and carbon dioxide:

Through their growth process, trees extract carbon dioxide from the atmosphere. Each year, a tree that grows sequesters a certain amount of carbon. Over the years, the tree can store a large amount of carbon in its tissue, but when the tree dies, most of the stored carbon is released back to the atmosphere through the decomposition process. In 2008, trees stored 113,437 tones of carbon, and the net carbon sequestered (after extracting the carbon released by decomposition) was 5,422 tones/year.

Gross annual carbon sequestration (tones) and its associated %, by land use:

Urban forest:	26,876 t	(23.7%)	Transport:	3,876 t	(3.4%)
Natural forest:	42,108 t	(37.1%)	Institutional:	3,452 t	(3.0%)
Residential:	9,764 t	(8.60%)	Commercial/Industrial:	328 t	(0.3%)
Multifamily residential:	21,014 t	(18.5%)	Intensive used zone:	6,020 t	(5.3%)
Total	**113,437 tones**				

Net annual carbon sequestration (tones/year) and its associated %, by land use:

Urban forest:	1,002 t/y	(18.5%)	Transport:	196 t/y	(3.6%)
Natural forest:	2,099 t/y	(38.7%)	Institutional:	- 64 t/y	(-1.2%)
Residential:	565 t/y	(10.4%)	Commercial/Industrial:	31 t/y	(0.6%)
Multifamily residential	1,282 t/y	(23.6%)	Intensive used zone:	311 t/y	(5.7%)
Total	**5,422 t/year**				

Trees species that sequestered the most net carbon per year and its associated %:

Quercus ilex:	1,373 t/year	(25.3 % of the entire population)
Platanus x acerifolia:	1,008 t/year	(18.6% of the entire population)
Pinus halepensis:	484 t/year	(8.9% of the entire population)

Trees and energy saving

Vegetation, and particularly trees, affects the urban microclimates due to air temperature reduction thanks to the shade, evapotranspiration, wind patterns change, boundary layer modification, etc. As a result, trees help to reduce energy consumption in buildings and consequently emissions from power plants.

But the result obtained here with the UFORE model is not accurate, the model has calculated the energy saving with the Californian climate, not with the Mediterranean climate currently characteristic of the city. At the same way, the model did not take into account the different types of residential buildings, or the different kind of energies used for heating or cooling the city. For these reasons, we do not include in this report the Ufore result's for the energy saving due to trees. Once the program will be able to analyze energy saving from cities outside United States, this simulation should be repeat.

INTRODUCTION

The Urban Forest Effects (UFORE) model is a software designed by the Forest Service of the U.S. Department of Agriculture based on more than 10 years of research. This model is presented as the most complete tool for analyzing the urban vegetation currently available, as it is capable of providing the most detailed results on the structure and functions of trees based on a wide variety of data applicable in any type of zone or area (city, neighborhood or open space). It is therefore a very useful tool in order to discover, manage, make decisions on and develop a good strategy concerning the trees present in a city.

http://www.ufore.org/

UFORE requires meteorological and pollution data (per hour and for a whole year), as well as a great deal of field data about the trees and shrubs present in the city. But, as studying and measuring each tree in Barcelona is a task that is almost impossible to carry out due to the financial resources and time that would have to be invested, work has been carried out on plots (representative samples) distributed all over the city, a normal procedure in studies using UFORE.

Many American cities (2/3 of all the cities studied) have used this model to find out about and evaluate urban forest. They include San Francisco, Atlanta, Baltimore, Washington, New York, Boston and Houston. However, there are also studies in China, in cities like Beijing and Ningbo; in Porto Alegre, Brazil; in Santiago de Chile, Chile; in Mexico City and, among many others, in Fuenlabrada, Spain. The majority of these studies are available on the website at the address http://nrs.fs.fed.us/units/urban/data. Some appear in the form of scientific papers and others as reports presented to the respective city councils, research centers or other institutions. This has made it possible to compare some of the results found for the city of Barcelona with other places where the model has already been applied.

Despite the fact that the study was carried out in 2009, meteorological and pollution data from 2008 have been used, so the results obtained largely correspond to 2008.

This study is structured as follows (the first 5 sections are the modules corresponding to the UFORE model):

1. **Urban forest structure** – based on the field data, the following aspects are quantified: 1) composition of species, number of trees, vegetation cover, tree density, trunk diameter distribution, 2) leaf mass and biomass; 3) ground cover; and 4) origin and diversity of species.
2. **Air quality** – in this section, based on the field data, pollution concentration and meteorological data, the model quantifies: 1) the quantity of the following pollutants removed from the air during the year: CO, O_3, SO_2, NO_2 and PM10; and 2) the annual economic value deriving from the improvement in air quality.
3. **Carbon sequestration and storage** – Based on the field data and allometric equations obtained from the literature, the following are calculated: 1) the total carbon stored; and 2) the gross and net carbon sequestered by shrubs and trees.

4. **Biogenic emissions (VOCs)** – based on the field data and meteorological data, the model quantifies: 1) hourly emissions of VOCs (monoterpenes, isoprene and other volatile organic compounds); and 2) formation of O_3 and CO based on VOC emissions. Using this data, it is possible to classify the species that have the best effect on air quality in Barcelona.
5. **Energy-saving** – this evaluates: 1) the effects of the trees on energy consumption in buildings; and 2) the consequent effects on carbon emissions.

Besides the UFORE model, other environmental services have been studied and evaluated in a general way, but in these cases there are no specific data of the city. These environmental services are:

6. **Noise pollution attenuation** – based on the report drawn up by Barcelona City Council (Evaluation of noise levels in the city's parks and gardens due to traffic, 2007), and the existing bibliography on noise reduction by vegetation.
7. **The urban water cycle** – based on the results obtained in other cities with UFORE-Hydro, CITYgreen or other simulation models capable of calculating this environmental service.

URBAN FOREST STRUCTURE

The basic premise of the UFORE model is that the urban tree structure determines its functions and value. So, with a precise evaluation of the structure, estimates will be obtained for the functions of the vegetation and the services it provides us with. The model uses a stratified random sample to estimate the different structural attributes of the trees measured within a known standard error.

Based on the field data obtained during the sampling, this first part quantifies the structure of the urban forest (understanding the urban forest as all the tree and shrub vegetation found in Barcelona, whether this consists of street trees, parks or gardens): soil (natural permeable or partially impervious in different ways), plant cover, composition of species, tree density, leaf area and biomass, tree health (according to the number of dead branches), diversity, geographical origin of species (and, therefore, climatic requirements) etc.

Once the measurements and all the structural information has been obtained from the field work in each sampled area, the model uses this data to calculate other structural values and incorporates environmental data to estimate multiple functional values dealt with in the following sections.

The methodology used to calculate the vegetation structure in Barcelona can be found in Appendix VII. For more details, consult the documents *UFORE methods* (2008) or *i-Tree user's manual* (2008), both available online.

AIR QUALITY

Air pollution caused by human activity has become a problem since the beginning of the industrial revolution. With the increase in population and industrialization, and largely as a result of increasing energy generation, industrial activities and the use of transport based on fossil fuels, large quantities of pollutants have been produced (ICTA 2002). This pollution appears particularly pronounced in urban centers, as is the case in Barcelona.

The main generators of air pollution and the causes of the presence of these gases in the urban atmosphere are transport, industry, electrical power generation, domestic heating and solid urban waste incineration. Transport in cities is responsible for more than 50% of air pollution. In the case of Barcelona, according to Servant (1996), the contribution from traffic could reach 60%. By contrast, the European Commission has announced that, in Europe as a whole, only 22% of greenhouse gas emissions are due to transport, but it is to be expected that the proportion would be much larger in cities.

In the last few years, various studies have been carried out establishing that air pollutants have damaging effects on human health. These harmful effects are largely related to the increase in respiratory and cardiovascular diseases, allergies and certain types of cancer (Künzli et al. 2007). According to a study by the Environmental Epidemiology Research Centre (CREAL), only in Barcelona it is estimated that 3,500 deaths a year are due to pollution. The damage is also translated into economic terms, largely due to the medical costs generated (Escobedo et al. 2008). Air pollutants also affect animal health, damage vegetation and materials, reduce visibility and solar radiation and, finally, affect the weather and the climate (McPherson & Simpson 1999). Urban vegetation, particularly trees, can affect environmental quality and human welfare either directly or indirectly. There are many studies (for example McPherson & Simpson 1999, Yang et al. 2005, Nowak et al. 2006 and Escobedo & Nowak 2009) showing that urban vegetation affects air quality at local and regional level by eliminating air pollutants, while altering urban microclimates due to the reduction in temperatures caused by shade and evapotranspiration, changing wind patterns, modifying the boundary layer, as well as reducing energy consumption in buildings and, therefore, the emissions generated by electric power plants.

The air purification effect can be caused aerodynamically, when the plant mass stands in the way of the wind and retains particles, or by capture, thanks to the capacity of some plant species for fixing particles. However, plants respond differently depending on the species and the maturity of the tree, the availability of water and nutrients and exposure to certain pollutants. Air pollutants can reduce the growth of shoots on seedlings and the growth in height of adult trees. In addition, the leaf area of trees exposed to certain pollutants can be reduced due to the inhibition of leaf formation, the halting of leaf expansion or the acceleration of leaf abscission (ICTA 2002). For this reason, it is very important to know the resistance of the trees in our city, as the evaluation of the current state of the urban trees in the city of Barcelona and their relationship with air pollution removal adds value to the conservation of urban forest, while encouraging investment in urban trees and their proper management in order to achieve environmental improvement.

In this report, when it comes to calculating the air pollution removal of vegetation, the following are taken into account: 1) the concentration of certain problematic pollutants present in our city – these are ozone (O_3), sulphur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2) and particulate matter less than 10μm (PM10) – based on the data collected at the different check points in the Barcelona air pollution monitoring network; 2) meteorology; and 3) the healthy leaf area of the urban vegetation in our city.

The methodology used is detailed in Appendix VIII. For more information, consult the documents *UFORE methods* (2008) or *i-Tree user's manual* (2008), both documents available online.

BIOGENIC EMISSIONS

One important aim of this research has been to provide information about the role of urban forest in forming air pollutants as well as removing them (Nowak et al. 2006). This is because, through the emission of Volatile Organic Compounds (VOCs), urban trees can contribute to the formation of tropospheric ozone (O_3) and carbon monoxide (CO). The potentially adverse effects of vegetation on air quality have therefore been taken into account, as well as the positive ones.

Photograph of Barcelona taken from the Carretera de les Aigües at 8:30 in the morning.

The tropospheric ozone generated, together with other compounds (nitrogen oxides, VOCs...), contributes to so-called photochemical smog, which is recognizable as a reddish brown mist like the one that can be seen in the photograph. This photochemical smog reaches its maximum extent during the summer months, with an increase in solar radiation and a reduction in air movement, creating more polluted atmospheres over cities.

VOCs (such as isoprene and monoterpene) emitted by certain trees into the atmosphere are natural chemical compounds making up essential oils, resins and other plant products that can be useful for trees in attracting pollinators or repelling predators (Kramer & Kozlowski, 1979; Nowak 1994a;

Nowak et al. 2002). The quantity of VOCs emitted depends on the species, the biomass of the leaves, the air temperature and other environmental factors, as well as the formation of O_3, which is created on the basis of chemical reactions between the VOCs and the NO_X present in the atmosphere, a reaction which is still more active if the temperatures increase (Nowak et al. 2000b). However, according to this author, in an atmosphere with a low NO_X concentration (for example, a rural area), VOCs can eliminate O_3. So, as VOC emissions depend on the temperature and trees generally reduce this, it is believed that, paradoxically, an increase in tree cover reduces the increase in overall O_3 emissions in urban areas (Nowak et al. 2002).

Many studies agree that a good strategy for helping to reduce ozone levels in cities is, therefore, increasing vegetation, particularly the species that emit less VOC (Nowak et al. 2000b). But, as Taha demonstrates, (1996) in a study carried out on the southern Californian coast, an increase in tree cover results in a reduction in O_3 when the trees planted emit few VOCs, as happens with *Fraxinus* spp., *Gleditsia* spp., *Malus* spp., *Prunus* spp., *Pyrus* spp. and *Sorbus* spp. When the trees planted emit greater quantities of VOCs, there is a local increase in O_3 (Benjamin et al. 1996). This is the case with the *Liquidambar*, *Eucalyptus*, *Quercus*, *Platanus*, *Populus*, *Rhamnus* and *Salix* genera, among others.

So, the choice of trees (and shrubs) is very important, as the local impact of the urban forest on air quality can be negative or positive. For this reason, in this report, apart from evaluating the concentration of pollutants absorbed by urban vegetation, species will also be classified depending on their capacity to improve the air quality in the city of Barcelona.

It also must be borne in mind that the air is a circulating fluid medium, although moments of relative stagnation can occur. The air flowing from the city towards peripheral rural or forest environments may, therefore, have effects we do not consider here, and, in the same way, the air flowing towards the city from the periphery can bring pollutants along with VOCs from nearby natural forest masses. Only part of the total balance can be altered by municipal management alone.

The methodology used to calculate the emission of Volatile Organic Compounds (VOCs) and the formation of tropospheric ozone (O_3) and carbon monoxide (CO), can be found in Appendix IX. For more details, consult the documents *UFORE methods* (2008) or *i-Tree user's manual* (2008), both documents available online.

GREENHOUSE GASES

Urban areas are population centers where large quantities of energy are consumed and the result of the consumption patterns of these towns and cities is the release of carbon dioxide (CO_2) and other greenhouse gases (GG), such as methane (CH_4), nitrous oxide (NO_2), tropospheric ozone (O_3) and others. These greenhouse gases undoubtedly contribute to the increase in air temperature at global level (GIECC 2007). The use of fossil fuels (72%), followed by industrial activities (13%) and agricultural activities, mainly deforestation (9%) are largely responsible for the increase in CO_2 in the atmosphere (GIECC 2007).

For Catalonia, according the scenarios and different models used – Coupled models from general atmospheric and oceanic circulation (AOGCM), but also simplified climate models (SCM) and earth simulation models of intermediate complexity (EMIC) – it would be necessary to wait until the end of the century to see an increase in the average temperature of 3.5ºC, with a more marked increase in summer than winter (4.1ºC and 2.6ºC respectively) (GIECC 2007).

Urban areas show climatic differences in comparison with more rural environments because of the so-called heat island effect resulting from the effect of the urban structure on air circulation, the materials used for construction, the use of fossil fuels and traffic.

One factor reducing the increase of CO_2 in the atmosphere is carbon sequestration by plants. Through the growth process, trees eliminate atmospheric CO_2 and accumulate it in their biomass (both aerial and subterranean) in the form of carbon (C). Carbon storage by trees is the process by which atmospheric CO_2 enters in the leaves via the stomata, combines with water and is converted into cellulose, sugars and other materials in a chemical reaction catalyzed by sunlight, thereby forming the wood, leaves and all the structures of the plant. The CO_2 stored is proportional to the biomass of the trees which, in turn, is affected by the crown cover, tree density and trunk diameter.

Carbon sequestration refers to the annual rate of CO_2 storage during a growing season. It therefore depends on growth and also on mortality which, in turn, depend on the composition of species and the age of the trees making up the urban vegetation.

Young woodland accumulates carbon rapidly for decades, then the annual increase in carbon sequestration declines (Harmon et al. 1990; McPherson & Simpson 1999). But in mature woodlands the quantity of CO_2 (coming from the decomposition of dead trees) can come to equal the quantity of CO_2 sequestered (McPherson & Simpson 1999). Meanwhile, although fast-growing trees initially sequester more CO_2 than slow-growing ones, this advantage can be lost if the fast-growing trees have a short life expectancy. An example of this are the results obtained by McPherson and Simpson (1999) who found that the CO_2 sequestered by the hybrid poplar, a fast-growing tree with a relatively short life, was 2,460kg in 30 years, while the CO_2 sequestered by the sugar maple (*Acer saccharum*), a slow-growing tree with a longer life expectancy, was 3,225 kg in 60 years.

It must not be forgotten that the loss rate of street trees is usually high in the first few years. Therefore, the survival of urban trees, as well as pruning, are important variables affecting long-term absorption. This is shown in a study carried out on the vegetation of Chicago, in which it was found that almost 15% of the CO_2 sequestered each year was released into the atmosphere through the decomposition of woody biomass from the pruning of trees and shrubs (Jo and McPherson 1995; McPherson 1998). **It is therefore very important to know the characteristics and needs of the tree (in terms of size and growth) to minimize the need for pruning and thereby reduce the release of carbon.**

According to McPherson and Simpson (1999), due to the high tree density, forest environments sequester up to twice as much CO_2 than urban trees per unit of area – between 4 and 8 t/ha. However, as urban trees grow more quickly than forest trees, at individual level, urban trees sequester more CO_2. In particular, urban trees in open spaces are the ones showing the greatest capacity to sequester CO_2, as they usually present considerable leaf biomass, a crown with greater exposure to light and face less competition from the nearest trees. To all this must be added irrigation, fertilizer and other factors leading to a high growth rate (McPherson and Simpson 1999).

When trees are stressed, for example during a hot summer or a spring with little rain, they can lose their normal CO_2 absorption capacity, as they are obliged to close their stomas as a defense mechanism to prevent water loss. Vigorous, healthy trees therefore absorb more CO_2 than sick or stressed trees (McPherson and Simpson 1999).

One of the keys for maximizing CO_2 sequestration is therefore the selection of species well adapted to the climate, the city and the place where they will be planted, as a tree not suited to the conditions that surround it will grow more slowly, suffer stress or even die at a young age. This species selection must also take into account the growth rate, life expectancy and maintenance required and, consequently, the ultimate destiny of the dead tree as, due to decomposition, it will gradually release the carbon stored throughout its life.

The methodology used to calculate carbon sequestration and storage can be found in Appendix X. For more details, consult the documents *UFORE methods* (2008) or *i-Tree user's manual* (2008), both available online.

MICROCLIMATE REGULATION AND ENERGY CONSUMPTION

Cities affect the local climate and even the weather. In fact, compared to peri-urban areas, solar radiation in cities is up to 20% lower and wind speed (urban breeze) between 10% and 30% less (Bolund and Hunhammar 1999). In addition, in Barcelona, according to Moreno (1993), the average annual air temperature can, in extreme conditions, come to be 8ºC higher in the centre (the Eixample district and surrounding area, for example) than on the periphery, with the temperature difference greater at night than during the day. This phenomenon, called the heat island effect, is principally caused by the large quantities of energy consumption in urban areas, in combination with the heat-absorbent area that exists in the city (Bolund and Hunhammar 1999). This heat-absorbent area is largely made up of asphalt and cement, materials that heat up much more during the day than areas of vegetation and which are very efficient in storing solar radiation. This will be converted into thermal energy, which is released at night in the form of heat.

Water helps to moderate temperatures in both winter and summer, but vegetation also plays a very important role due to its physiological function. Plant species release humidity into the environment – humidity from the water that they have extracted from the soil via their roots. This process, called transpiration, helps to cool the environment around the tree, as a single mature tree can transpire as many as 450 litres of water a day (Bolund and Hunhammar 1999). Evapotranspiration can reduce the ambient temperature, particularly when the humidity is low, but not all species provide the environment with the same amount of humidity. In general, leafy species (such as silver birch, oak or beech) are the ones that release most water vapor compared with others.

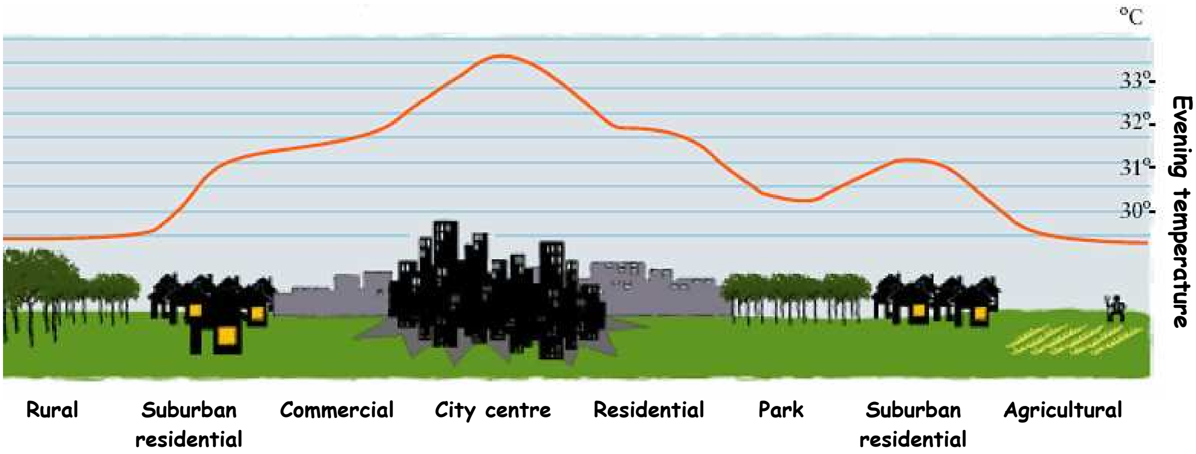


Figure 1. Diagram of a heat island profile.

Source: Akbari et al. (1992), amended and adapted for this report.

Thanks to the shade offered by trees in the city, as well as the previous function, tree cover causes a reduction of temperatures in the hottest months (Bolund and Hunhammar 1999), thereby moderating energy consumption deriving from the use of air conditioning. In winter, trees reduce the wind speed and vegetation can also substantially reduce energy use from heating (Bolund and Hunhammar 1999), but evergreens, with their shade, can have a contrary effect.

In Chicago (United States), for example, it has been demonstrated that, with a 10% increase in tree cover, or by planting 3 mature trees per block of flats, the cost of the total energy needed to heat and cool a two-storey building can be reduced by €60 per year per home (McPherson et al. 1997; Bolund and Hunhammar 1999).

As well as the problem deriving from the increase in temperatures in the city, the heat island effect is related to another environmental problem, the production of smog, as high temperatures speed up the formation of both smog and tropospheric ozone, which form a pollution cloud above cities that retains heat (as has been seen in the section on biogenic emissions).

The methodology used is detailed in Appendix XI. For further information consult the documents *UFORE methods* (2008) or *i-Tree user's manual* (2008), both available online.

ATTENUATING NOISE POLLUTION

In most towns and cities, noise pollution is considered as a very important environmental factor directly affecting the quality of life of their inhabitants. This pollution derives directly from the activities carried out by humans in the city, such as transport, the construction of buildings, industry or certain leisure activities, which can come to cause an irritating noise capable of having harmful physiological and psychological effects on people. These harmful effects include sleep disorders, tiredness, hearing loss, stress, anxiety and other disorders that disturb people's health.

According to the World Health Organization (WHO), the desirable noise limit – measured in decibels (dB) – outside houses is 55dB in the daytime and 44dB at night, but this value is exceeded in many areas and at numerous points in the city of Barcelona. In some cases, noise can come to exceed 100dB; that is, according to McPherson (2000), up to double the level at which noise can become a health risk. Table 1 shows the different levels of human response and some examples of noise intensity levels, expressed in decibels.

One technical solution for reducing noise pollution at the most problematic points is the construction of 3-5m high noise insulation screens, which reduce noise levels by 10-15dB (that is, a sensation of noise reduction of more than 50%) immediately behind them. But, apart from the cost involved, the installation of acoustic screens in all affected areas would completely change the look and the perception of the city. For this reason, this report has included the effect of vegetation on noise reduction so that alternative, ecological measures for dealing with the problem can be suggested.

Table 1. Noise levels and human response.

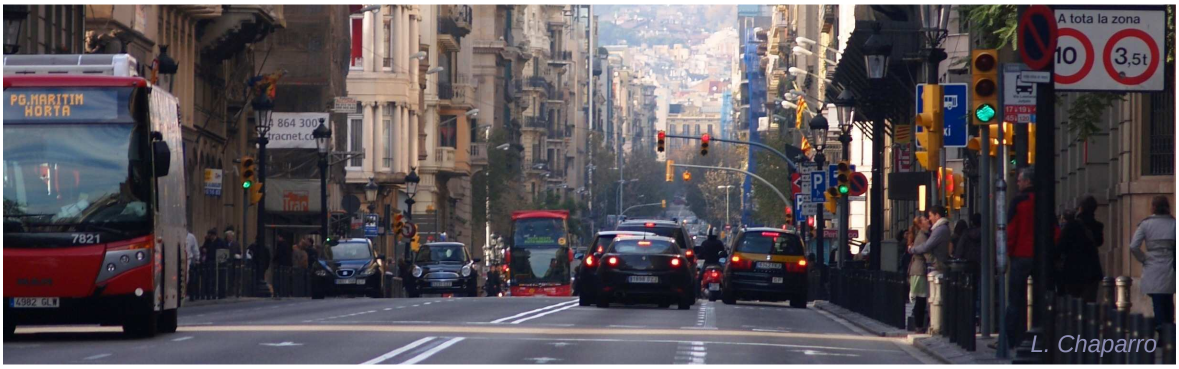
Some examples of noise level	dB	Human response	Damage
Missiles	180	Irreversible loss hearing	Sever hearing damage
Rocket launch	160		
Operation of jets, aircraft	140	Painfully strong	
Volcanic eruption, thunder, orchestra of 75 musicians	130		
Waterfall, jackhammer, rock concert	120	Maximum vocal effort	Danger of temporary deafness, headache
Hurricane, chain saws, car in the highway	110	Extremely strong	
Big storm, fireworks, truck	100	Very hard	
Storm, urban traffic, subway	90	Very annoying	
Waves, noisy street, wake	80	Harassing telephone use	Hard feeling
Normal voice, rain, restaurant	70	Intrusive	
Air conditioning, conversation at 1 meter	60	Quiet	Possible fatigue
Computer fan, office background sound	50		
Voice near the ear, lounge	40	Very quiet	Calm
Library, bedroom	30		
Leaves movement, radio studio, clock	20	Almost no audible	
Flight of a mosquito, whisper at 1 meter	10		
Absolute silence	0	Threshold of hearing	

Source : Querol J.M. (1994), amended and adapted for this report.

Trees and plants in general affect noise attenuation in different ways: through absorption (eliminating the noise), deviation (altering the direction of the noise), reflection (returning the noise to its origin), refraction (when the sound waves circulate around the vegetation) and occultation (when an irritating noise is changed into a pleasant sound) (CONAMA 2002).

However, determining the point to which vegetation contributes to reducing noise is difficult as, as well as the complex effect of vegetation in attenuating noise pollution, the type and duration of the noise, the distance of the source of the noise from the receiver, the soil material, the atmospheric conditions such as the wind direction, the temperature gradient, the relative humidity (the higher the humidity the greater the attenuation) and the topography of the ground must all be taken into account.

In a wood, for example, the sound waves are reflected and refracted by the trees, causing the sound energy to be dispersed through the branches and trees, which can even absorb sound energy in the viscose and thermal layer near the surface of the plant (Bucur 2005). Leaves substantially reduce sound transmission, particularly at high frequencies (where dispersion is greater). By contrast, the ground reduces a large quantity of the lower frequencies of sound energy through absorption, and the effectiveness of these increases as the soil becomes more porous (Aylor 1972).



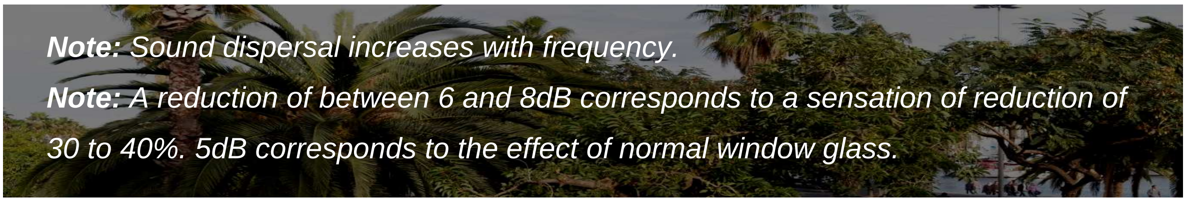
According to Aylor (1972), with an increase in leaf density and the breadth and the thickness of leaves, the effect of foliage is increased. Other authors have also confirmed that broadleaved trees are better at reducing noise than conifers and that the most effective trees are those with large, leathery leaves, even more so when they are orientated perpendicularly to the source of the noise (Maillet 1993).

When foliage is not very dense, noise reduction is largely due to the branches (Aylor 1972), mainly for medium frequencies. The level of reduction will therefore depend on the species, the diameter and type of bark on the trunk, the height, the number of trees per unit of ground area, dispersal and absorption, crown leaf area and the species making up the undergrowth (Bucur 2005), apart from many other factors already mentioned, including the distance from the source of the noise, the soil type, the atmospheric conditions and the ground topography.

Many authors, including Miller (1997) and Aylor (1972), agree on the fact that plants absorb high frequencies more than low ones. This fact is an advantage for human beings, as the highest frequencies are the ones that most affect people and cause most stress (Miller 1997).

Roadside trees, with high leaf density, make sound disperse and reduce the reverberation effect on façades or other hard areas of the noise caused by wheeled traffic (Maillet 1993). But, **for optimum noise reduction, the trees and shrubs would have to be planted near the origin of the noise and not near the receiving area, which, in the case of street trees, is almost the same. In addition, it would be desirable a diversity of high-density evergreen trees and shrubs species with a dense foliage** (Bucur 2005).

In woods, parks or gardens, another important effect is added, the masking of noise by plants through the substitution of pleasant sounds to cover up the unpleasant ones, as nature has its own sounds, such as leaf movement and bird song.



Note: *Sound dispersal increases with frequency.*

Note: *A reduction of between 6 and 8dB corresponds to a sensation of reduction of 30 to 40%. 5dB corresponds to the effect of normal window glass.*

THE URBAN WATER CYCLE

Man affects the natural water cycle in two different ways: directly, though water extraction and the possible release of polluted water, and indirectly, by altering the vegetation and ground cover. Both ways alter the water circulation system and its quality.

As a result of extensive urban development, the large quantity of smooth, asphalted surfaces alters the surface drainage of water in cities, where up to 90% of rainwater can be lost, as it goes directly into the sewerage network (Higueras 2006). Meanwhile, in areas with vegetation, only 5-15% of water drains away, with the rest evaporating, soaking into the soil (Bolund and Hunhammar 1999) or being stored in tree branches and leaves. The existence of the sewerage network and large impermeable areas not only affects the levels and quality of the aquifers, it also influences the local climate, as it reduces the evapotranspiration of the soil and the plants living on it.

In addition, the concentration of SO_2 in the atmosphere means the rain in cities is likely to be very acid, with a pH of less than 3, a factor increasing the acidification of the soil and damaging the growth of vegetation in urban and industrialized environments (Higueras 2006).

Despite the fact that there has been a considerable change over the last few years in Barcelona in awareness concerning water saving, generally in cities like ours there is a considerable alteration in surface drainage and a waste of rainwater which quickly disappears from the environment as it runs off towards the urban sewerage network.

Pollution, largely emitted by vehicles, accumulates on roads, in car parks and on other surfaces. This pollution includes engine oil and petrol, fertilizer, pesticides and heavy metals, which are carried by the rain into nearby watercourses. In addition, the larger the impervious surface, the greater the speed and volume of polluted run-off water. This can cause serious damage to ecosystems, displacing pollution-sensitive flora and fauna as well as leading to an accumulation of pollutants in sediments and increased soil erosion (ICLEI 2006).

So, in terms of the urban water cycle, trees also offer very important environmental services, as they help to keep pollutants out of watercourses, sometimes filtering them directly into their own organisms through their roots, thereby improving water quality. At the same time, they help to reduce the volume of run-off water, as follows:

1. Tree leaves and branches have large areas capable of temporarily retaining considerable quantities of water (for between 10 and 20 minutes according to McPherson et al. 2000), until the tree crown is saturated and the water flows down the stems and trunk to the earth or evaporates directly into the atmosphere;
2. The roots and permeable soil beneath or directly around the tree also store large quantities of rainwater, as, unlike compact soil, it allows the water to soak in more quickly due to the fact that the roots make the soil spongy, increasing water penetration;

3. The trees act as a natural filter by retaining sediments and organic material from the run-off;
4. With the existence of multiple layers of tree and/or shrub crowns, the impact of raindrops on the soil is reduced, helping to reduce erosion.

In addition, trees absorb humidity from the soil surface through evapotranspiration, thereby increasing the soil's water storage capacity (USDA Forest Service, 2002).

So, thanks to their water retention capacity, trees – as well decomposing biomass and grass areas, among others – increase the soak away rate and water retention capacity, reduce the surface flow of rain by cutting the run-off caused above all by small-scale storms (which are responsible for "cleaning" or "carrying off" the largest percentage of pollution) and thereby reduce the risk of flooding and water pollution.

METHODOLOGY

Sampling

The 101km^2 (Barcelona including Collserola) of the study zone have been classified into different land uses. To make this stratification, the latest edition of the Ecological Map of Barcelona (Burriel, J.A.; Ibáñez, J.J.; Terradas, J. 2006) has been used, amended and adapted to our study case. The 29 existing land use types in the third edition of the ecological map have been grouped and simplified into 8 categories.

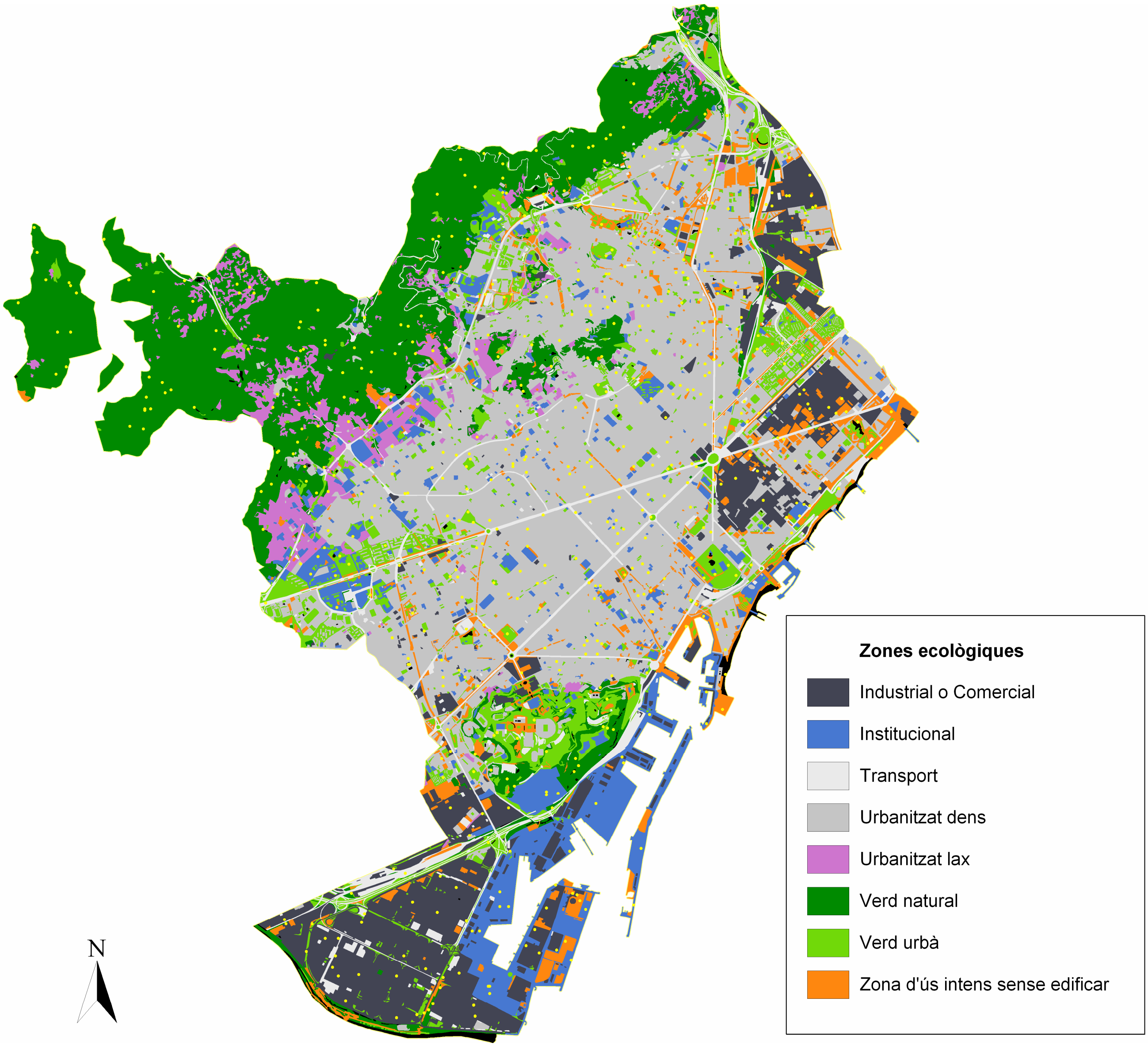
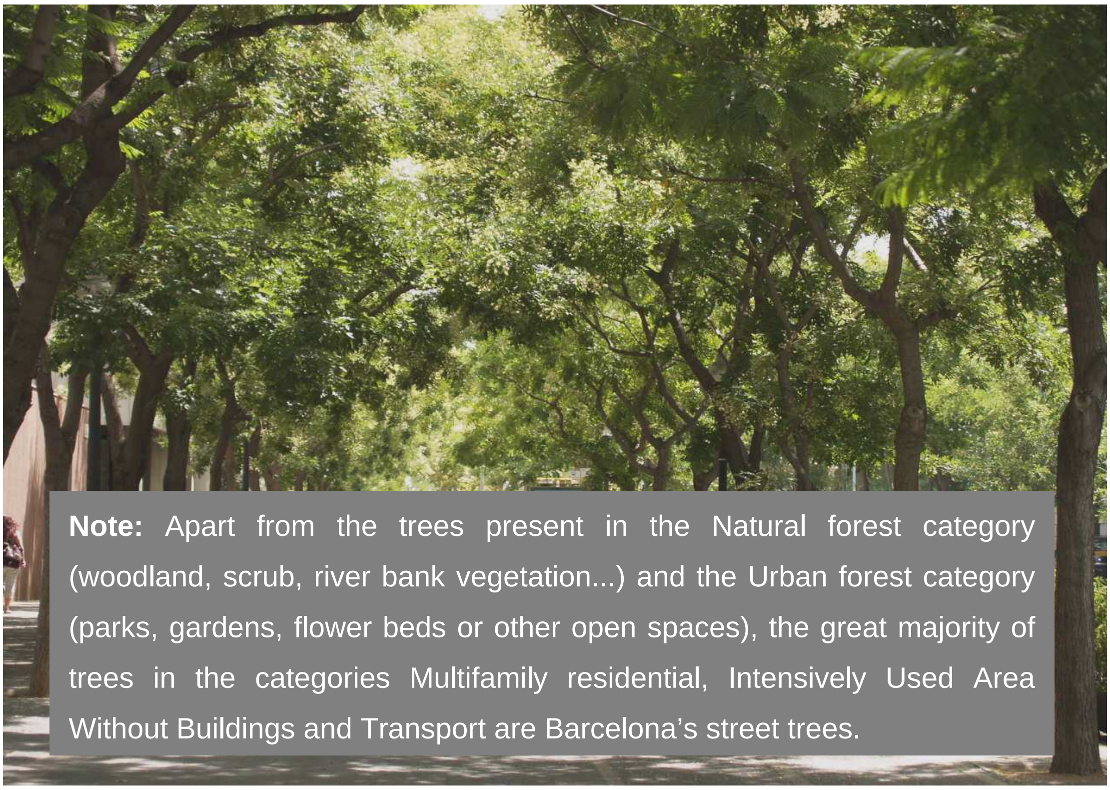


Figure 2. Plot distribution within each ecological area.

These 8 ecological zones, shown in Figure 2, correspond to:

- **Urban forest:** Park, garden, flower beds or other open spaces;
- **Natural forest:** Woodland, scrub, meadow or riverbank vegetation;
- **Residential:** 1- to 2-family residence — low density residences;
- **Multifamily residential** or mixed residence and commercial: multifamily buildings (three or more dwelling units) or in mixed residential and commercial buildings;
- **Transport:** Car parks and depots, main urban roads or railway area;
- **Institutional:** Hospital, cemetery, education centre or port area;
- **Industrial or commercial:** Industry, workshop, warehouse or large shopping area;
- **Intensively used area without buildings:** Pedestrian area, area without buildings or area undergoing transformation.



Note: Apart from the trees present in the Natural forest category (woodland, scrub, river bank vegetation...) and the Urban forest category (parks, gardens, flower beds or other open spaces), the great majority of trees in the categories Multifamily residential, Intensively Used Area Without Buildings and Transport are Barcelona's street trees.

To apply the UFORE model, we were recommended to study 250 circular plots measuring 404m^2 (which means a radius of 11.34m), in accordance with the UFORE protocol (Nowak et al. 2005). After consulting many reports and articles on other cities where the model has been developed, and taking into account that Barcelona is a compact, densely built up city and that many of the points could fall on roofs, in the middle of motorways or in other places without vegetation, the number of plots chosen to carry out this study was finally set at 579, each measuring 404m^2. The total area studied was 23ha, spread throughout the city, with an approximate density of one plot for every 17.4ha.

Once the stratification had been carried out (based on the ecological map of Barcelona) and the number of plots to be studied determined, the 579 plots were distributed randomly, by applying the Miramon program, in each of the different ecological zones, with more plots allocated to zones with a larger areas (Table 2).

Table 2. Area and name of the plots analyzed by ecological zone.

Ecological zones	Surface in hectares	Number of plots
Urban forest:	806	50
Natural forest:	2,184	125
Residential:	424	20
Multifamily residential:	3,666	204
Transport:	513	30
Institutional:	776	39
Commercial/Industrial:	1,185	70
Intensive used areas without building:	567	41
Total	**10,121**	**579 plots**

Field data

Based on the 1:5,000 ortho-images in natural color from the Cartographic Institute of Catalonia, ICC (2004), each plot was classified depending on whether it had trees, shrubs or an herbaceous layer in order to identify the sampling zones without vegetation, as no field work needed to be carried out there.

In the sampling areas with vegetation present, technical sheets were drawn up for each plot, which information such as street names, addresses, GPS coordinates and a detailed map corresponding to an ortho-image with sufficient resolution (0.5m) indicating the centre and the sampling area within which the measurements would be taken, as can be seen in the following images extracted using the Miramon program:

The plots with vegetation present were visited for 3 months (from May to July) by a team of 2 people. The general data collected during the field work were:

1) General information (Table 3) to identify the plot, as well as its main characteristics;
2) Information about the shrubs (Table 4), used to estimate the leaf area and shrub biomass, the pollution eliminated and the emission of volatile organic compounds (VOCs). To collect the data, shrubs of the same species and height were grouped into the same set and the data shown in Table 4 was noted for each group (species, height, leaf mass lost...).
3) Tree information (Table 5), used to estimate the structural attributes of urban woodland, pollution removed, VOC emissions, carbon sequestered and stored and the effects of the trees on energy saving in buildings. The information contained in table 5 (species, height, diameter...) was collected for each tree inside the plot.

Table 3. General plot information.

Variable	**Description**
Plot ID	Unique identifier (between 1 to 579 studied plots)
Date & team	Date and name of each crew member
Plot address and GPS coordinates	Address ands coordinates of global positioning system at plot center
Actual Land use	Land use determined on the plot (Residential, Multifamily residential, Transport, Commercial/Industrial, Institutional, Intensive used areas...)
Plot tree cover	Amount of tree canopies covering the plot. This datum is the proportion of the sky that is obscured by tree crowns within the plot and will range from 0 to 100%.
Plot shrub cover	Percent of the plot area covered by shrub canopies
Ground cover	Proportion of the plot ground area covered by the following materials: buildings, cement, tar, other impervious material, soil, rock, duff/mulch, herbaceous, grass, wild grass or water
Plantable space	Percent of the plot area that is plantable for trees (i.e., plantable soil that is not filled with tree canopies above (or other overhead restrictions) and tree planting would not be prohibited due to land use (e.g., footpath, baseball field, etc.)

A shrub is considered as:

Any kind of woody plant with a diameter of less than 2.54cm.

An herbaceous plant is considered as:

Any kind of plant with a height below 30.45cm.

Table 4. Shrub information.

Variable	**Description**
Specie	If not know note genus
Height	Height (m, to nearest 1/10th) of the shrub mass for the species
Percent area	Of the total ground area of all shrubs on the plot, what percent of the ground area is occupied by this species/height combination
Percent shrub mass missing	Of the volume of this species/height combination, the percent of the volume that is missing, i.e., not occupied by leaves

Table 5. Tree information.

Variable	**Description**
Tree ID	Unique tree number. Start at 1 and assign sequentially.
Distance and direction	Distance (in meters) and direction (in degrees azimuths) from plot centre to the tree
Specie	Specie name (A, C, E, S, V)
DBH	Diameter of each living and dead tree at breast height (1.35m) on the uphill side of tree, measured in cm (C, S)
Total height	Height to top (alive or dead) of tree measured in m. Tree height must be recorded for all trees, including dead trees (A, C, E, S, V)
Height to crown base	Height to base of live crown measured in m. Record dead trees as 0 (A, S, V)
Crown width	Crown width in m. Crown width is recorded by two measurements: N-S (North-South) and E-W (East-West) widths. Dead trees always have a crown width of 0 (A, S, V)
% canopy missing	Percent of the crown volume that is not occupied by leaves. Within the "typical crown outline" estimate the percent foliage that is absent (A, S, V)
% dieback	Percent crown dieback in crown area. This dieback does not include normal/natural branch dieback/pruning due to crown competition/shading in the lower portion of the crown. However, branch dieback on side(s) of crown area due to shading from a building or another tree would be included (C, E, S)
% impervious	Percent of land area beneath entire tree canopy's drip line that is impervious. If tree crown crosses out of plot boundary, entire area beneath tree is still estimated (H)
% shrub	Percent of land area beneath canopy drip line that is occupied by shrubs. If tree crown crosses out of plot boundary, entire area beneath tree is still estimated
Crown Light Exposure (CLE)	Number of sides of the tree receiving sunlight from above. Top of tree is counted as one side. 0 to 5 sides (C, S)
Direction and distance to building	Direction to building. For trees (>= 20 ft. tall) that are located within 60 feet of space conditioned residential buildings that are 3 stories (2 stories & attic) or less in height, record the direction (azimuth) to the closest part of the building. This should be noted in degrees (E)
Street tree	Y if a street tree; N if not a street tree.
Variable used to study: A = Pollution removed; C = Carbon sequestration; E = Energy conservation; S = Structure information; V = VOC emissions.	

RESULTS

Note: *To avoid confusion due to the large quantity of data introduced into the model and subsequently processed both by the USDA Forest Service and ourselves, American numbering has been used in drawing up this report, using the full stop "." to indicate decimals.*

Note: *For information on calculations, see appendices VII to XI.*

Note: *For information on vocabulary, consult the glossary in appendix XII.*

Urban forest structure

The urban vegetation of Barcelona is made up of 1,419,823 trees (194,340 of which correspond to trees planted in the city's streets and squares, covering 2,535 hectares (25.20% of the area of Barcelona including Collserola). The species composition obtained based on the field work is 138 species of trees and 35 shrubs. The trees with a DBH of less than 23cm make up 70.6% of the population. The 4 most common species are: *Quercus ilex* (22.1%), *Pinus halepensis* (20.5%), *Platanus x acerifolia* (6.6%) and *Pinus pinea* (4.9%). More information about the species and number of trees can be found in Appendix I.

Among the different land uses, the greatest tree densities come in the categories Natural forest (377 trees/ha), Urban forest (264 trees/ha) and Residential (205 trees/ha), as can be seen in Figure 4. This last category corresponds to housing for one or two families with garden that are usually found in the higher part of Barcelona or in the urban developments in Collserola, with a garden or plot of land often very similar to those found in Natural forests. The land uses in the categories Intensively used area without buildings (corresponding for the most part to pedestrian areas), followed by Multifamily residential and Transport, owe their tree density (87, 61 and 55 trees/ha respectively) to the street trees present on a large number of Barcelona's pavements.

A large part of the tree population (48%), as can be seen in Figure 5, is in the diameter category between 2.5 and 15cm, followed by the diameters 15.1 to 30cm (38.1%) and 30.1 to 45cm (10%). Industrial is the land use with most young trees, and therefore with small diameters, while Institutional, followed by Transport and Intensively used area without buildings, show the greatest proportions of individuals with large diameters.

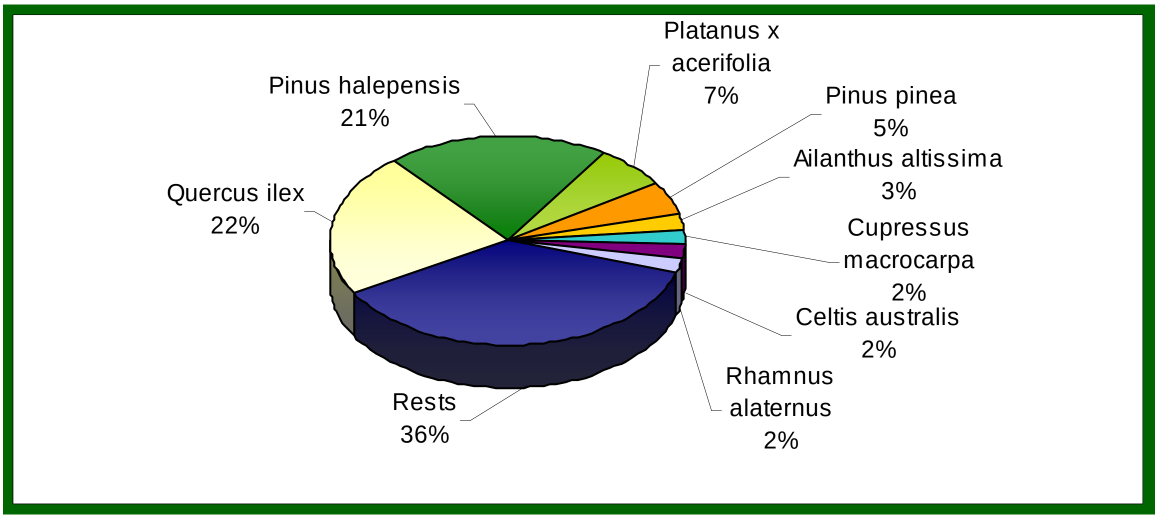


Figure 3. Composition of tree species.

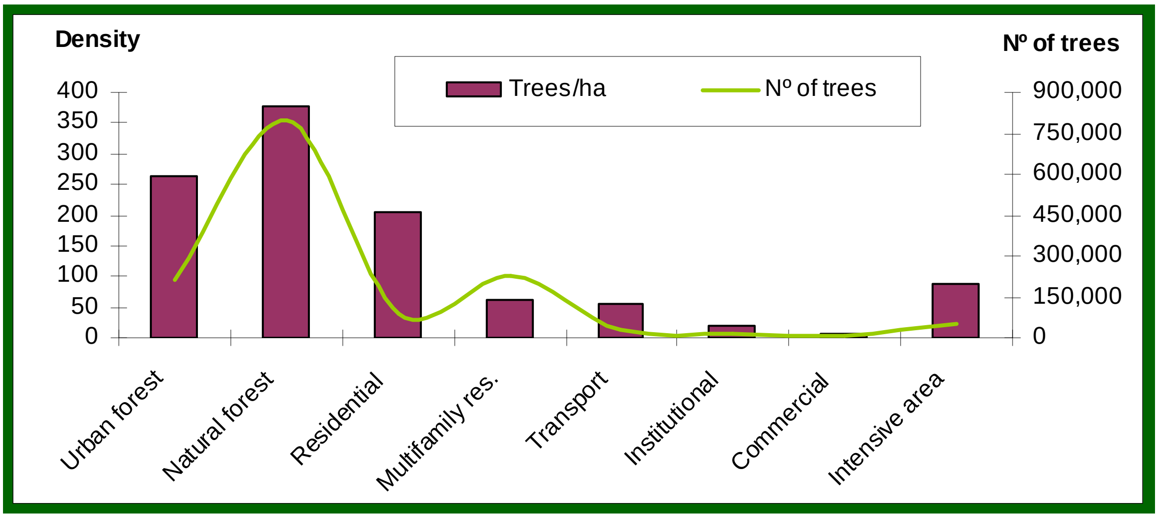


Figure 4. Tree density (trees/ha) and number of trees by land use.

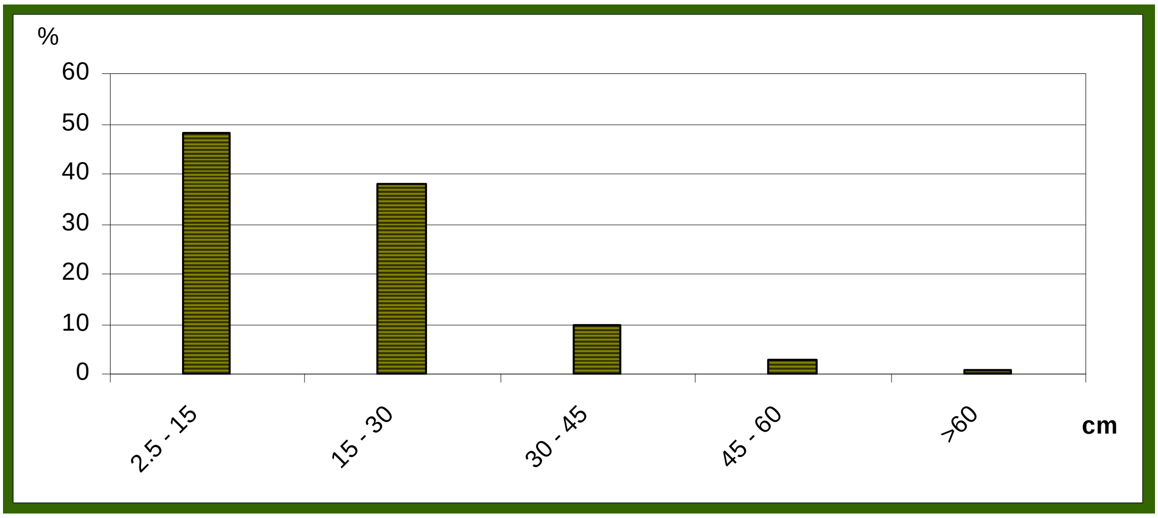


Figure 5. Percentage of the tree population according to DBH (cm).

Tree, shrub and ground cover

The majority of the area of Barcelona is occupied by buildings (31.5%), tar (17.6%) and cement (14%), and these impermeable materials make up 64.1% of the total area, while the remaining 36% is permeable soil (13.7% sand, 19.2% herbaceous, 2.8% grass and 0.3% water), as can be seen in Figure 6.

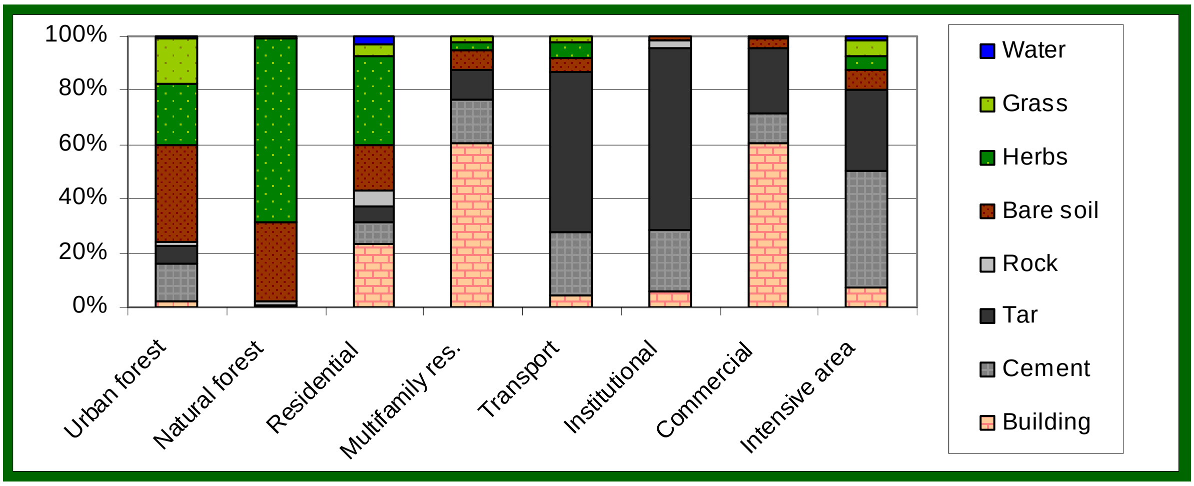


Figure 6. Ground cover by land use type.

The plant cover of the area of the municipality of Barcelona is made up of 25.2% trees and 7.3% shrubs. But when the soil is permeable and there are no tree crowns impeding the growth of new trees (that is, when it is grass, herbaceous cover or soil) and tree planting/establishment would not be prohibited due to land use (e.g., footpath, baseball field, etc.), this space has been listed as plantable space. In total, this represents only 3.6% although **this figure would allow the planting of more than two hundred thousand new trees, mostly in Urban forest and Intensively Used Areas without buildings.**

The greatest tree cover, as can be seen in Figure 7, corresponds to the Urban forest category (56%), followed by Natural forest (50%), Residential (43%) and Intensively Used Areas without Buildings (25%). The fact that Natural forest does not have greater tree cover is due to the fact that, in the entire sampling area in Collserola Natural Park, apart from woodland of Holm oak, Aleppo pine and Stone pine, there are large areas of scrub, meadow, crag, natural river bed and bare forest floor, occupying a total of 704ha, that is 32.3% of all Natural forest.

The tree density per hectare and land use follow almost the same pattern as the tree cover, with Natural forest with the greatest density, followed by Urban forest and Residential. The land use showing least cover and tree density is Industrial or Commercial.

As the plots were chosen randomly, on many occasions the study zone did not show any vegetation (47% of cases - 273 occasions), in which case only the type of ground cover in the plot has been noted.

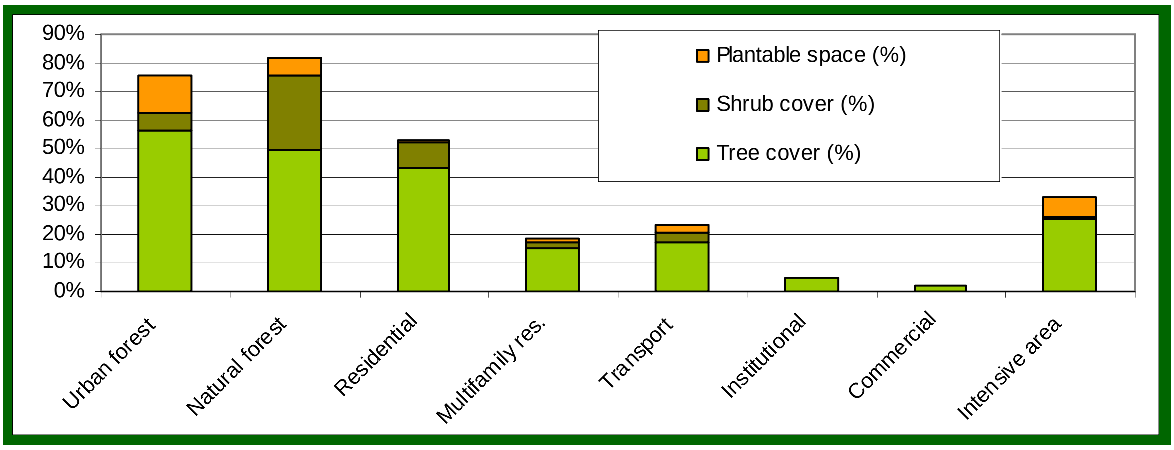


Figure 7. Tree cover, shrub cover and plantable space by land use.

Origin and diversity of species

Urban trees consist of a mixture of native and exotic species. For this reason, Urban forest often shows greater diversity of species than that found in more natural areas. The increase in biodiversity can minimize the impact (or destruction) by a specific insect or disease on a particular species or genus, but it can also involve a risk to native plants if any of the introduced species behaves as an invading species, as these can come to compete with or displace the autochthonous species.

In Barcelona, 19% of the species are of Mediterranean origin, 11% European, 13% Eurasian and 3% horticultural species, with the remaining 54% from other continents. However, if we are referring to the number of individuals, Barcelona has 62% of individuals of Mediterranean origin, 5% of European origin, 3% of Eurasian origin and 7% of horticultural varieties. 23% of the remaining individuals are exotic species (2% from Africa, 10% from America and Asia and 1% from Australia and New Zealand), as can be seen in Figure 8.

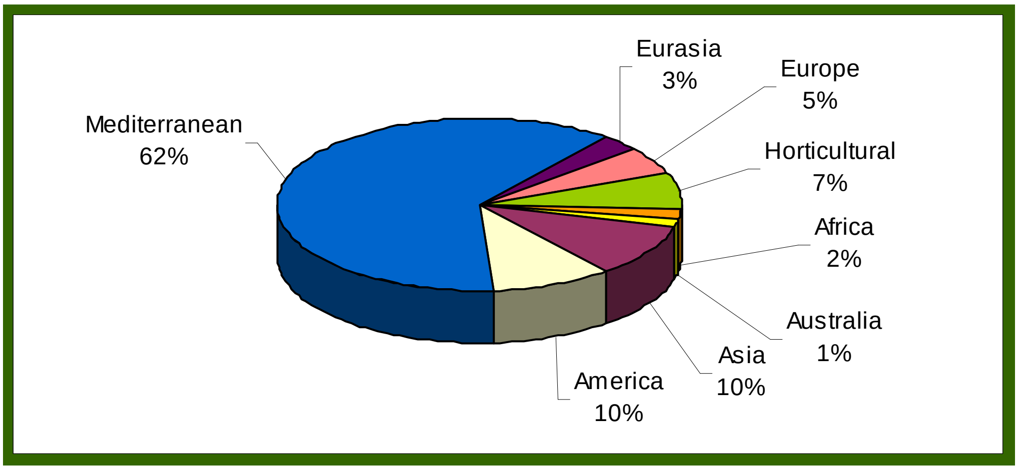


Figure 8. Origin of individuals.

The categories Urban forest, Multifamily residential and Intensively used area without buildings are the ones that show most exotic species (52.8%, 52.3% and 40.5% respectively), with approximately half the population individuals from other regions, largely Asia and America, while the categories Natural forest, Residential, Transport and Institutional are largely made up of individuals of European, Eurasian or Horticultural species, as can be seen in Table 6.

Table 6. Percentages of individuals according to their origin and land use.

	Africa	America	Asia	Australia	Eurasia	Europe	Horticultural	**Total EXOTIC**
Urban forest	5.3%	22.6%	22.6%	2.2%	7.7%	30.3%	9.2%	**52.8%**
Natural forest	0.1%	1.7%	3.9%	0.2%	0.8%	92.9%	0.4%	**5.9%**
Residential	6.3%	10.3%	5.7%	2.3%	2.9%	66.1%	6.3%	**24.7%**
Multifamily residential	2.6%	24.9%	21.5%	3.2%	3.4%	23.0%	21.3%	**52.3%**
Transport	5.8%	13.0%	8.7%	0.0%	1.4%	33.3%	37.7%	**27.5%**
Institutional	0.0%	0.0%	0.0%	14.3%	0.0%	85.7%	0.0%	**14.3%**
Comm./Industrial	28.6%	0.0%	0.0%	0.0%	7.1%	21.4%	42.9%	**28.6%**
Intensive areas	4.1%	20.9%	12.2%	3.4%	0.7%	38.5%	20.3%	**40.5%**

As for the exotic species found in Barcelona, these include some naturalized ones: trees such as *Acer negundo*, *Agave americana*, *Arundo donax*, *Sophora japonica*, *Aloe arborescens,* or shrubs such as *Senecio angulatus* or *Genista canariensis*. There are also other species acting as invaders, such as *Acacia dealbata*, *Elaeagnus angustifolia*, *Eriobotrya japonica*, *Eucalyptus camaldulensis*, *Eucalyptus globulus*, *Gleditsia triacanthos, Parkinsonia aculeata*, *Schinus molle* and *Ulex parviflorus*, as well as *Ailanthus altissima*, *Opuntia ficus-indica* and *Robinia pseudoacacia*, catalogued according to DAISIE (Delivering Alien Invasive Species In Europe) among the top 100 invasive species in Europe (or among the top 18 terrestrial plant species).

An important point to analyze, regardless of the origin of the species, is the ideal climate they belong too, based on the very simplified categories of different types of climate by Navés Viñas et al. (1992). The plots studied have shown that more than 90% of individuals are in an ideal climate or a sub-climate very similar to the typical Mediterranean climate currently characteristic of the city. These sub-climates of the Mediterranean climate are: subtropical Mediterranean climate (hotter and with tree species such as *Eucalyptus globulus* and *Eucalyptus camaldulensis*; or shrubs as *Aloe arborescens* and *Nerium oleander*); semi-arid subtropical Mediterranean climate (with less rain including species such as *Maclura pomifera*, *Casuarina equisetifolia* or *Washingtonia filifera*); Mediterranean mountain climate (damper and cooler, with species such as *Prunus cerasifera*, *Quercus cerrioides*, *Pinus radiata* or *Pinus pinaster*); continental Mediterranean climate (with more extreme temperatures and species like *Juniperus phoenica*) and, finally, Atlantic Mediterranean climate (damper, and with species such as *Platanus x acerifolia*, *Populus alba, Tilia tomentosa, Acer negundo, Ulmus pumila* and many others, such as *Ailanthus altissima*).

Diversity in Barcelona has been calculated using two different indices: the richness of species (S), which is the number of species sampled within each ecological zone, and the Shannon-Wiener (H') index, which is calculated based on the number of species present in an area (richness of species) and the relative quantity of each one of these species (abundance). In most natural ecosystems, the Shannon-Wiener index varies between 0 and 5, although there can exceptionally be ecosystems with higher values.

The result is shown in Figure 9, where it can be seen that the Intensively used area without buildings (S=148 and H'=16.47), Multifamily residential (S=84 and H'=3.6) ─ categories with greater presence of street trees ─ and Urban forest (S=77 and H'= 3.6), are the ones showing the greatest wealth of species and a higher Shannon-Wiener index, while the Residential (S=33 and H'=2.4) and Natural forest categories (S=57 and H'=2.1) show intermediate values. By contrast, the Institutional category shows the lowest diversity values (S=2.7 and H'=0.67), as it is dominated by the Cupressus species populating the majority of cemeteries.

The Intensively Used Area has obtained values similar to those of tropical forests, but we must understand that the significance of this is quite different: a natural forest is an ecosystem where there are functional interactions between the species, whereas a plantation can have as many species as we like represented by a single individual, and therefore enormous diversity without ecological significance.

In total for the city, the richness of species (S) was 138 trees and 35 shrubs, with an average Shannon-Wiener index of 3.27. So, as might be expected, the ecological zones or land uses with most species from other continents are also the ones showing greatest diversity. For this reason, the Urban forest category shows a greater diversity of species than Natural forest.

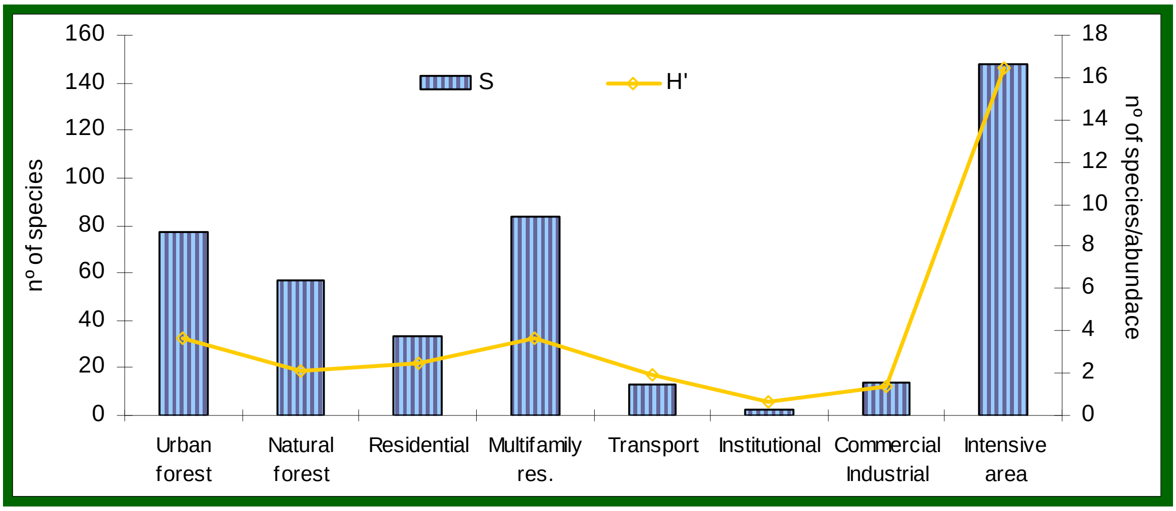


Figure 9. Diversity index by type of land use.

Leaf Area and Biomass

Barcelona's total leaf area (trees and shrubs) is 130km^2, with Natural forest (61km^2), followed by Urban forest (25km^2) and Multifamily residential (23km^2) the areas with the greatest leaf area. But if we are talking about leaf density (of both trees and shrubs) Urban forest shows the greatest area per hectare (31,377m^2/ha), followed by Natural forest (28,588m^2/ha) and Residential (18,563m^2/ha).

Total leaf biomass (shrubs plus trees) follows the same pattern as leaf area: Natural forest is in first position (5,538t), followed by Urban forest (2,032t) and Multifamily residential (1,691t). The land uses with the greatest biomass density per hectare are

Natural forest (2,608kg/ha), Urban forest (2,522kg/ha) and Residential (1,783kg/ha), as shown in Figure 10.

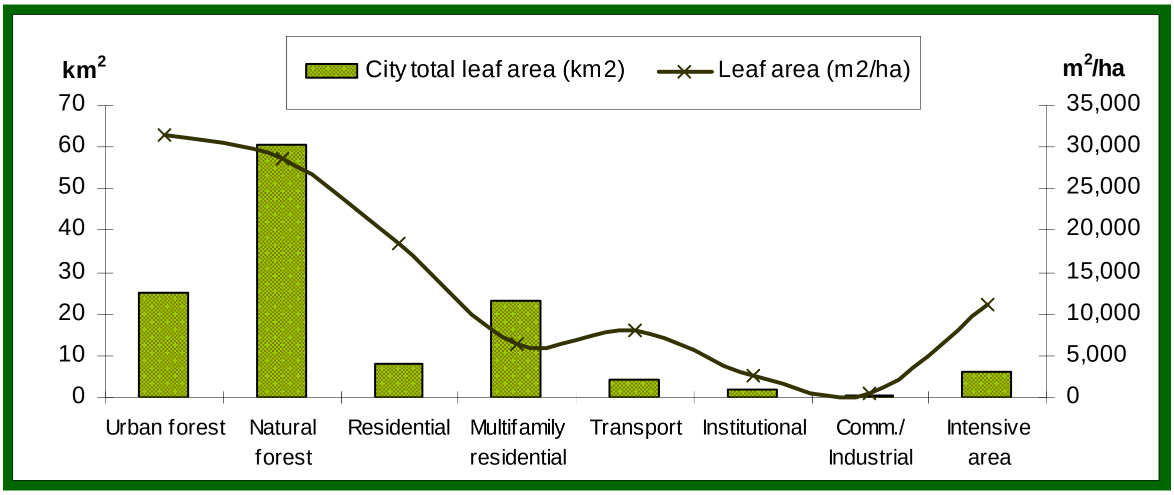


Figure 10. Leaf area and leaf area per hectare according to the type of land use.

The different values for leaf area and leaf area density for each land use, including both shrubs and trees, appear in Table 7.

Table 7. Leaf area (km^2) and leaf area density (m^2/ha) for trees and shrubs.

	Leaf area (km^2)		Leaf area density (m^2/ha)	
	Trees	Shrubs	Trees	Shrubs
Urban forest	21.6	4.0	26,823	4,554
Natural forest	31.6	29.0	14,897	13,691
Residential	5.8	2.0	13,629	4,934
Multifamily residential	19.2	4.0	5,245	1,053
Transport	3.8	0.0	7,385	653
Institutional	2.0	0.0	2,631	0
Comm./Industrial	0.5	0.0	406	0
Intensive areas	6.1	0.0	10,817	192
Subtotal	90.7	39.1	9,015	3,890
Total	130 km^2		12,906 m^2/ha	

In Barcelona, the most important species according to the number of trees are: *Quercus ilex* (22.1%), *Pinus halepensis* (20.5%) and *Platanus x acerifolia* (6.6%). But, as many of the benefits contributed by trees are directly related to the healthy leaf area of the plant, if we classify the trees based on leaf area, the order of importance changes and *Platanus x acerifolia* (22.4%) moves into first position, followed by *Pinus halepensis* (17.2%) and *Quercus ilex* (11%), as indicated in Table 8. The details of the total leaf area and biomass of all the species can be found represented in Appendix I.

Table 8. The most important species according to total leaf area and biomass.

	Nº of trees		Leaf area (km^2)		Leaf Biomass (t)	
	N	%	N	%	N	%
Platanus x acerifolia	93,212	6.6%	20.3	22.4%	887.2	11.6%
Pinus halepensis	290,525	20.5%	15.6	17.2%	1,502.6	19.6%
Quercus ilex	313,372	22.1%	10.0	11.0%	916.1	11.9%
Pinus pinea	69,749	4.9%	5.8	6.3%	554.9	7.2%
Celtis australis	30,529	2.2%	5.0	5.5%	292.8	3.8%
Robinia pseudoacacia	25,694	1.8%	2.3	2.5%	123.7	1.6%
Tipuana tipu	20,518	1.4%	2.2	2.4%	165.0	2.2%
Cupressus sempervirens	28,601	2.0%	2.2	2.4%	504.8	6.6%
Phoenix canariensis	15,716	1.1%	1.4	1.6%	242.5	3.2%
Ailanthus altissima	37,473	2.6%	1.2	1.3%	86.2	1.1%
Total	925,389	65.2%	65.9	72.6%	5,275.9	68.8%

At individual level, the 10 species showing the largest leaf area, this time expressed in m^2, are represented in Table 9. These species include *Cedrus deodara*, *Eucalyptus camaldulensis*, *Tilia europaea*, *Platanus x acerifolia*, or *Tilia euchlora*. The details of the leaf area and biomass per individual can be found represented in Appendix II.

Table 9. The most important species according to leaf area and biomass per individual.

	Nº of trees		Leaf area (m^2)		Leaf Biomass (kg)	
	N	%	N	%	N	%
Cedrus deodara	812	0.1%	420.0	4.9%	98.4	11.0%
Eucalyptus camaldulensis	1,172	0.1%	319.1	3.7%	44.1	4.9%
Tilia europaea	2,734	0.2%	267.0	3.1%	12.4	1.4%
*Platanus x acerifolia**	93,212	6.6%	218.0	2.5%	9.5	1.1%
Cocculus laurifolius	1,172	0.1%	206.5	2.4%	15.3	1.7%
Tilia euchlora	3,460	0.2%	201.4	2.4%	9.4	1.1%
Morus alba	843	0.1%	193.4	2.3%	14.1	1.6%
Casuarina equisetifolia	2,259	0.2%	188.1	2.2%	20.8	2.3%
Pinus pinaster	4,425	0.3%	165.2	1.9%	15.9	1.8%
*Celtis australis**	30,529	2.2%	162.7	1.9%	9.6	1.1%
Total	140,618	10.1%	2341.4	27.3%	249.6	28.0%

****Note:*** *For a species to be considered relatively important in the population it has to contribute at least 1% of the total population. So, within this group of relatively important species, in Barcelona there are only 19 species. The other 119 do not reach 1% relative abundance.*

Leaf area estimates are adjusted according to the physical condition of the tree, that is, the percentage of dead branches (crown dieback). Each tree measured during the field work was classified according to the percentage of crown dieback, into one of the seven possible classes of condition: excellent, good, fair, poor, critical, dying or dead tree. For this reason, the lower the number of dead branches, the more individuals and the greater the trunk diameter, the greater the leaf area.

As can be seen in Figure 11, this was the case for all diametric classes, except for trees between 15.2 and 22.8cm DBH, as this category shows larger proportions of trees in normal, poor or dead conditions (25.3%, 9.1% and 1.5% respectively) compared to the other diametric classes. The details of the total leaf area and biomass of the species is represented in Appendix I and the details at individual level are in Appendix II.

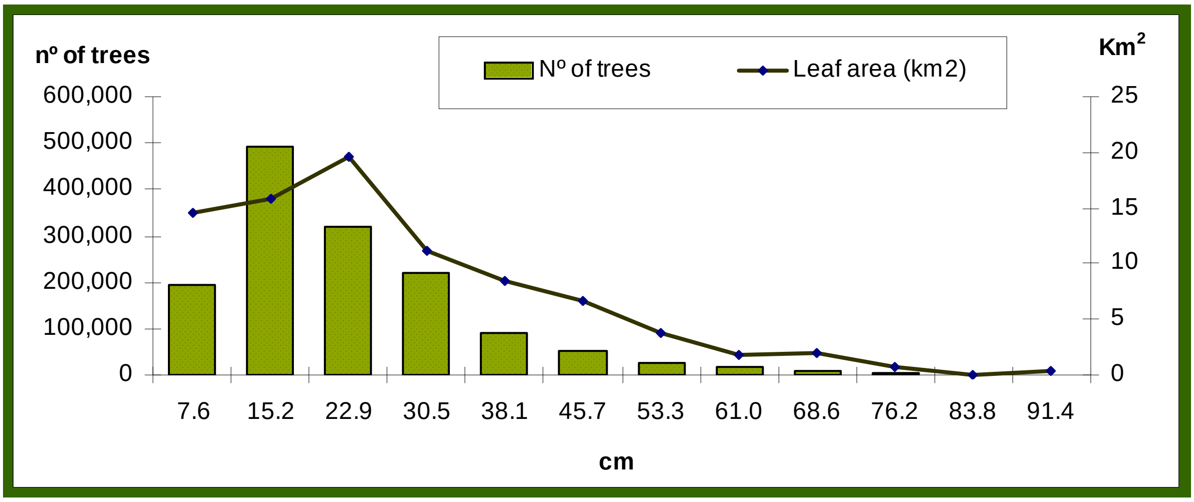


Figure 11. Number of trees and leaf area (km^2) according to the DBH.

Air quality

The pollution eliminated by the vegetation during the night is minimal because the stomas are closed. Therefore, in calculating the elimination of O_3, SO_2, NO_2, CO and PM10, only the pollution produced during the day and during the period with leaves has been taken into account. **In 2008, Barcelona's trees and shrubs have depurated 305.6t of pollution from the air. From an economic point of view, this purification is valued at €1,115,908 a year**. As can be seen in Figure 12, 54.3% of the pollution eliminated corresponds to PM10 (166t), 23.8% to O_3 (72.6t), 17.9% to NO_2 (54.6t), 2.2% to SO_2 (6.8t) and, finally, 1.8% to CO (5.6t).

The distribution of these pollutants throughout the year is represented in Figure 13. As was to be expected, the removal and percentage improvement of the air shows daily and monthly variations due to the weather conditions and the vegetation, as well as the atmospheric concentration of pollutants. A large part of the pollution is eliminated during the months from April to August, with July being the month with greatest air depuration.

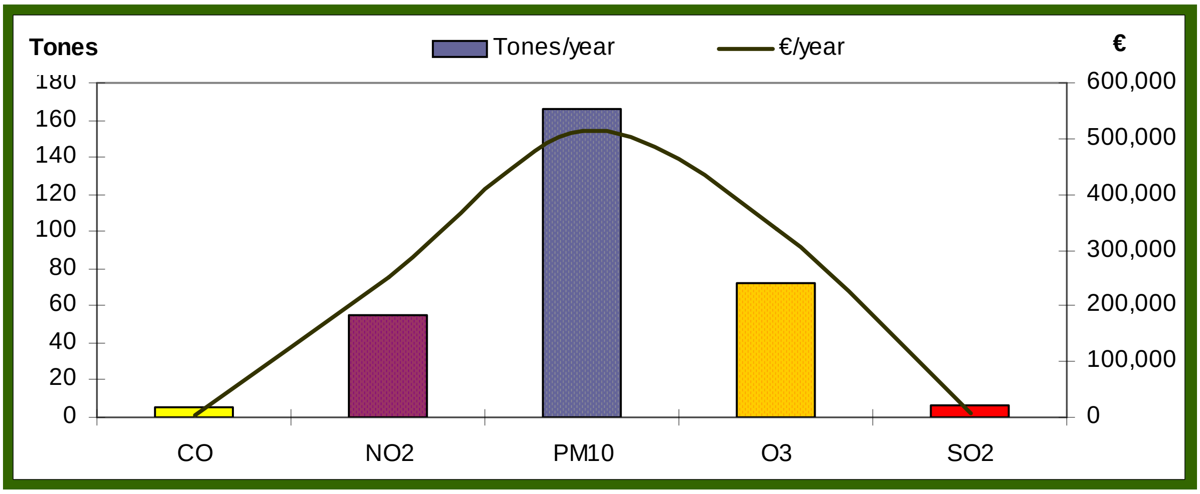


Figure 12. Estimated air pollution removal and associated economic value by trees and shrubs.

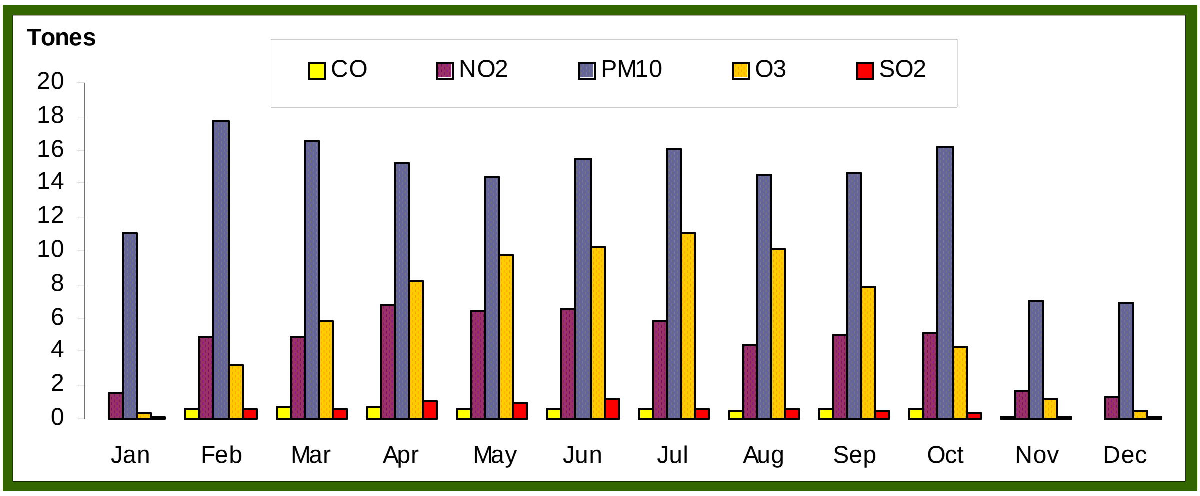


Figure 13. Monthly pollutant removal by trees and shrubs.

Based on the data passed on by the Barcelona air pollution monitoring network, there is strong correlation between air pollution in Barcelona and the pollution removal. For this reason, in the hottest months, when Barcelona shows the greatest concentration of O_3 in its environment, the purification of this pollutant is also greater. This applies to all pollutants except PM10, which shows high proportions all year round, although in January, November and December they reduce considerably.

Biogenic emissions

During 2008, Barcelona's trees and shrubs emitted 184t de VOCs (95t of isoprene, 36t of monoterpenes and 53t of other VOCs, such as ethane, propene, butane, acetaldehyde, formaldehyde, acetic acid and formic acid). Of the total emissions, 14.5% correspond to emissions generated by shrubs. The vegetation produces an average 6.2g of VOCs per m^2 of tree cover and 3.6g of VOCs per m^2 of shrub cover. As can be seen in table 10, land uses are ordered according to VOC quantities as followed: Natural forest, Urban forest, Multifamily residential, Residential, Intensively used area without buildings, Transport, Institutional and, finally, Industrial or Commercial.

Table 10. Annual emissions (kg) of isoprene, monoterpenes and other VOCs by land use.

	Isoprene	Monoterpenes	Other VOCs	Total VOCs
Urban forest	16,778	4,938	9,648	31,365
Natural forest	38,791	23,655	24,868	87,313
Residential	8,815	1,933	4,062	14,810
Multifamily residential	17,090	3,203	7,886	28,179
Transport	4,193	571	1,243	6,006
Institutional	908	1,178	2,690	4,776
Commercial/Industrial	1,127	10	158	1,294
Intensive areas	7,655	580	2,001	10,236
TOTAL	95,357	36,067	52,555	183,979

But, if we calculate VOC emissions per m^2 of plant cover for each land use, the Institutional category becomes the one generating more VOCs (both trees and shrubs) per square meter of plant cover (13.4g/m^2), followed by Natural forest and Residential (8.3 and 8.1g/m^2 respectively), Intensively used area without buildings (7.1g/m^2), Urban forest (6.9g/m^2), Transport (6.7g/m^2) and, finally, Industrial (6g/m^2) and Multifamily residential (5g/m^2).

Total VOC emissions in standardized conditions (at 30ºC and with a PAR of 1000 µmol/m^2/s^1) per m^2 of plant cover are 7.4mg C/m^2/h^1 for trees and 2.6mg C/m^2/h^1 for shrubs.

In Figure 14 it can be seen how the emissions of these chemical products vary over the year, with the highest emissions during the hottest months, largely July and August. They also vary throughout the day, as can be seen in Figure 15, where the maximums are between 10am and 2pm.

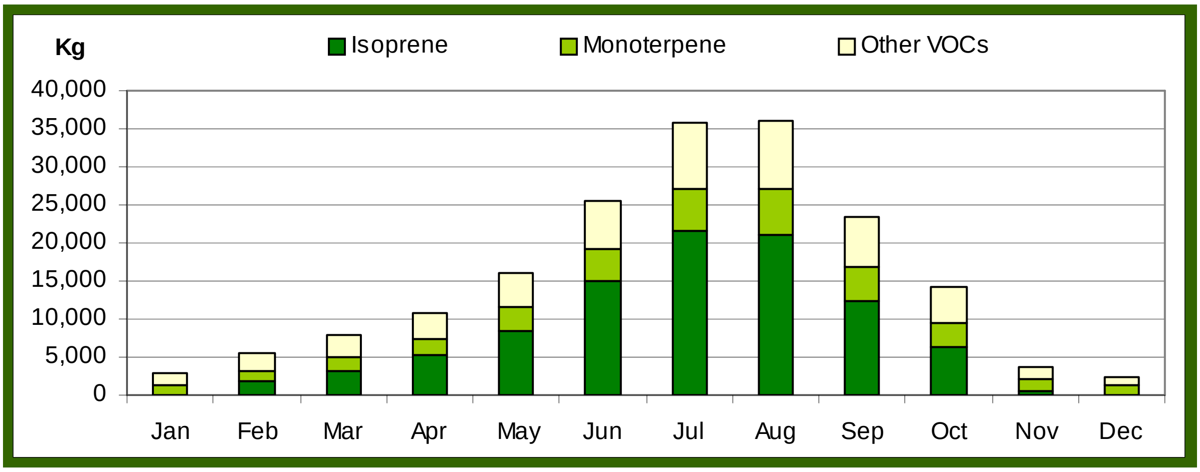


Figure 14. Monthly average VOC emissions produced by vegetation.

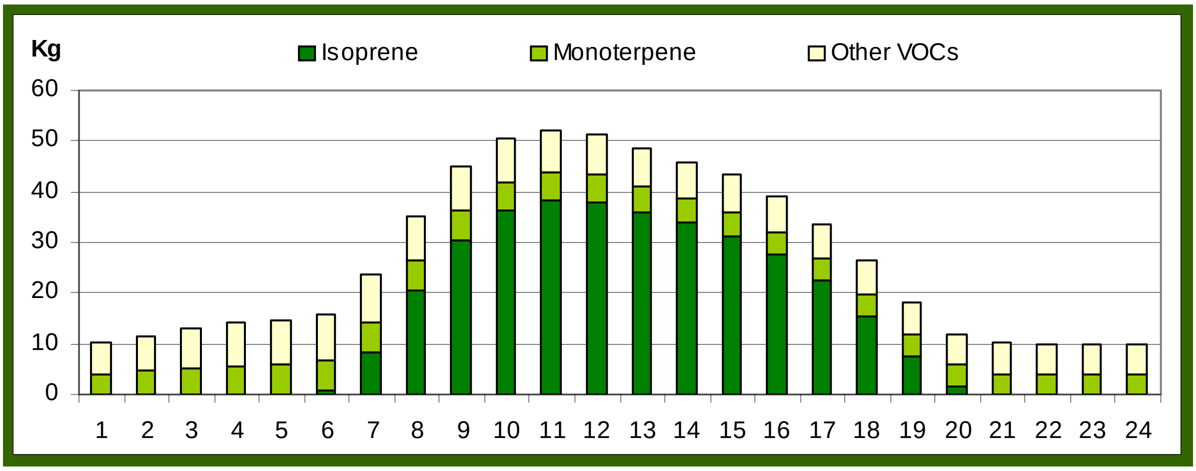


Figure 15. Hourly average VOCs produced by the vegetation.

Biogenic emissions have been calculated for 72 genera of trees and shrubs of the 114 genera present in this study. Three genera emitted 68% of total VOCs. These are: *Quercus* (27%), *Platanus* (21%) and *Pinus* (20%). Now, if we analyze the VOCs emitted per kg of leaf biomass, the genera emitting most VOCs are: *Eucalyptus*, *Casuarina*, *Robinia* and *Populus*, followed by *Platanus*, *Quercus*, *Salix* and *Koelreuteria*, as shown in Appendix III.

So, **if we are interested in reducing the formation of O_3 in our city, priority should be given to the species emitting least VOCs and, therefore, forming less O_3 and CO**.

Generally, the genera of trees that form least VOCs (per kg of leaf biomass) are:

- *Hibiscus*, *Tilia*, *Firmiana*, *Pyrus Jacaranda*, *Malus*, *Fraxinus*, *Prunus*, *Ulmu*s, *Melia* and *Sorbus*, as well as shrubs like *Pyracantha*, *Sambucus*, *Rosa, Lonicera*, *Rubus* and *Viburnum*. The genera generating least VOCs represent 40% of the total leaf biomass.

The genera forming most VOCs (per kg of leaf biomass) are:

- *Eucalyptus*, *Casuarina*, *Robinia*, *Populus*, *Platanus*, *Quercus*, *Salix* and *Koelreuteria*, among the trees, and *Pistacia*, *Rhamnus* and *Myrtus*, among the shrubs. In Barcelona, the species generating most VOCs make up 60% of the total leaf biomass (Appendix III).

Meanwhile, the genera forming smallest net quantities of CO net per kg of leaf biomass are:

- *Pyrus*, *Tilia*, *Jacaranda*, *Catalpa*, *Ligustrum*, *Fraxinus*, *Tamarix, Ulmus*, *Prunus*, *Laurus* and *Melia,* among the trees and *Sambucus*, *Pyracantha*, *Pittosporum*, *Viburnum*; *Rosa*, *Cottoneaster* and *Arbutus* among the shrubs. These genera represent a total of 38% of leaf biomass.

Those forming greatest quantities of CO are, above all:

- *Eucalyptus, Robinia, Populus, Casuarina, Platanus, Quercus* and *Salix,* among the trees, and *Pistacia*, *Rhamnus* and *Myrtus* among the shrubs. They make up 62% of the leaf biomass in Barcelona (Appendix IV).

The genera that eliminate most O_3 per kg of biomass are:

- *Pyrus*, *Firmiana*, *Tilia*, *Jacaranda*, *Catalpa*, *Fraxinus*, *Ligustrum*, *Tamarix*, *Ulmus*, *Ligustrum*, *Melia*, *Prunus*, *Celtis* and *Cupressus*, among other trees and *Sambucus*, *Pyrancantha* and *Pittosporum* among the shrubs. These genera represent a total of 41% of leaf biomass.

And the genera forming most O_3 per kg of biomass are:

- *Robina*, *Populus*, *Casuarina*, *Platanus*, *Quercus*, *Pinus*, *Eucalyptus*, *Phoenix* and *Salix,* among the trees, and *Rhamnus*, *Myrtus* and *Mahonia*, among the shrubs. These account for a total of 59% of Barcelona's leaf biomass (Appendix V).

So, with the results obtained, a ranking can be created of the species that improve air quality in Barcelona by weighting the individual species or genera according to the pollutants produced and the leaf biomass of the species or particular genus.

Carbon storage and sequestration

Barcelona's trees stored 113,437t of carbon (C) and sequestered 6,187 tones during 2008, but, due to returns through death and pruning, the trees of Barcelona finally removed 5,422 net tones of carbon from the atmosphere, as can be seen in Table 11. By contrast, if we study the net carbon density sequestered per hectare the Residential category is in first position, with net C values sequestered and stored greater than those for Natural forest, as can be seen in Table 12. In last position we find the Institutional category, which has negative net C values sequestered due to the dead individuals it contains.

Table 11. Leaf biomass, Carbon storage and Carbon sequestration by land use.

	Leaf biomass (t)	Net C Storage (t)	Gross C sequestration (t/year)	Net C sequestration (t/year)
Urban forest	1,674	26,876	1,088	1,002
Natural forest	2,940	42,108	2,446	2,099
Residential	556	9,764	613	565
Multifamily residential	1,366	21,014	1,398	1,282
Transport	240	3,876	207	196
Institutional	450	3,452	76	-64
Commercial/Industrial	30	328	32	31
Intensive areas	416	6,020	328	311
Total	7,672	113,437	6,187	5,422

Table 12. Net carbon stored and sequestered by hectare and land use.

	Net C Storage (kg/ha)	Net C sequestration (kg/year/ha)
Urban forest	33,345.0	1,243.7
Natural forest	19,834.1	988.9
Residential	23,027.6	1,331.7
Multifamily residential	5,732.1	349.7
Transport	7,555.2	381.6
Institutional	4,448.9	-82.0
Commercial/Industrial	276.8	25.9
Intensive areas	10,616.6	548.1
Total	11,208.0	535.7

The ecological zones storing most carbon in their trees are Natural forest (37% of the total C stored by trees), Urban forest (24%) and Multifamily residential (19%), as can be seen in Figure 16.

In Barcelona, trees with a diameter of more than 83cm sequester 30 times more C than trees smaller than 8cm, or 4 times more than trees with 31cm diameter. As can be seen in Figure 17, the trees that store and sequester most carbon are those with the greatest diameter.

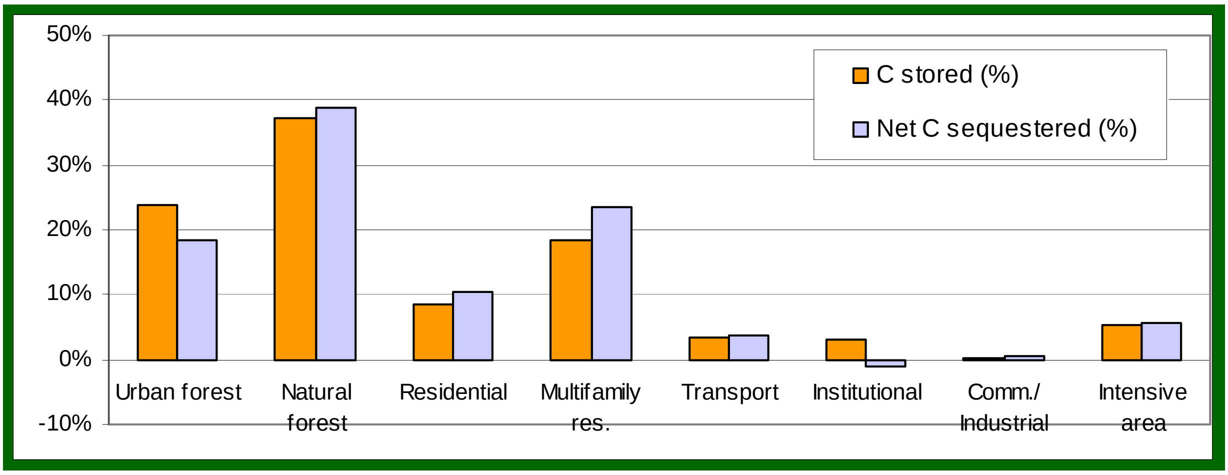


Figure 16. Percentage of carbon stored and sequestered by land use.

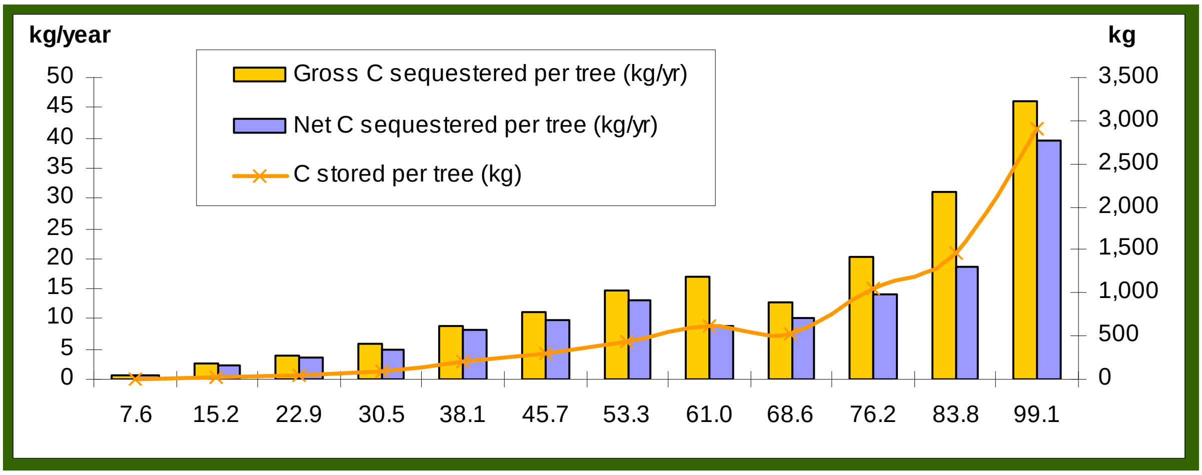


Figure 17. Carbon stored and sequestered per individual, according to DBH.

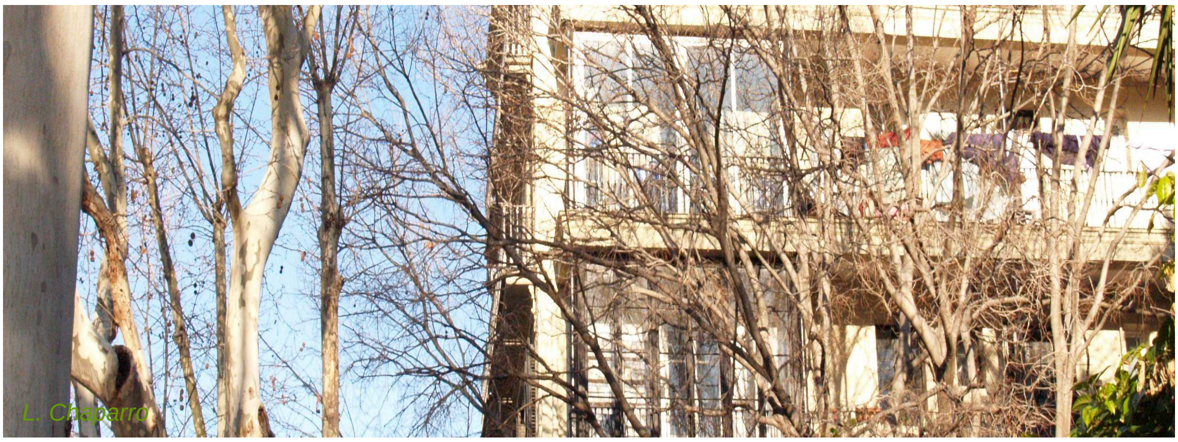
The tree species that currently store most carbon in the Barcelona area are: *Platanus x acerifolia* (21.6% of total C stored), *Quercus ilex* (18.5%), *Pinus halepensis* (14%), *Pinus pinea* (4.3%) and *Celtis australis* (2.8%). See Appendix I for the complete list of all trees included in this study. But, at individual level, the trees that sequester and store most carbon in a year are: *Eucalyptus camaldulensis* (8.7%), *Phoenix dactylifera* (4.73%), *Cocculus laurifolius* (3.32%), *Aloe arborescens* (2.14%), *Phytolacca dioica* (2.24%), *Platanus x acerifolia* (1.9%), *Salix alba* (1.77%) and *Populus x canadensis* (1.76%). See Appendix II.

Microclimate regulation and energy consumption

Thanks to the shade offered by the city's trees, the tree cover causes a reduction in temperatures during the hottest months, thereby moderating energy consumption deriving from the use of air conditioning in first- and second- floor flats (as trees do not usually have any effect on the upper floors). In Barcelona, and above all in the Multifamily residential land use, where there is greater density of housing and street trees, the energy reduction thanks to trees could be very considerable.

In many cities it has been shown that, in winter, trees reduce the wind speed, so vegetation can also substantially reduce energy loss from heating, but shade from trees, due to the presence of evergreens or their inappropriate positioning with respect to housing, can cause an increase in heating costs.

In this section, the results obtained with the UFORE model have not been reliable, as the model is not based on the particular Mediterranean climate characterizing our city but rather on the Californian coastal climate. It has also not taken into account the different types of buildings characterizing Barcelona or the city's particular type of energy consumption. For this reason, we could not include the results in this report.



Noise pollution

The data on the role of vegetation in relation to noise are diverse and often contradictory. The results of some research carried out have indicated that:

1. A plantation 30m wide, with tall and dense trees, can reduce noise by 50%, equivalent to a reduction of 10dB or more (Cook 1978);
2. Evergreen trees are better at attenuating noise that deciduous trees, and deciduous trees better than grass without trees (Martens and Huisman 1986);
3. Trees and other plants combined with an uneven landscape give reductions of 6-15dB (Miller 1997);
4. To reduce noise pollution in a city, belts at least 12m wide are required (Martens 1981);
5. 100m of dense vegetation reduces the noise level by only 1-2dB (Kommunförbundet 1998);
6. Strips of dense vegetation, in conjunction with the shape of the terrain or screens (solid barriers) can reduce the noise from a motorway by 6-5dB (McPherson 2000);
7. Evergreen trees are capable of attenuating 17dB for every linear 100m of vegetation; deciduous trees can attenuate only 9dB (Higueras 2006);
8. Open spaces or areas with a strip of peripheral vegetation of 7-17m reduce the noise level reaching the park. This noise level is minimized when shrubs 2-3m high are planted (Bucur 2005);
9. A dense screen of conifers 30m wide can absorb between 6 and 8db (Bucur 2005);
10. Sufficiently dense tree plantations can reduce noise by between 5 and 10dB (Barcelona City Council Noise Pollution Reduction and Monitoring Department).

Noise level in Barcelona's parks

In 2006, Barcelona City Council drew up a report to evaluate noise levels due to traffic in the city's parks and gardens. This work was carried out by combining simulation (obtaining isophone curves at a height of 4m) and long and short term field measurements as checks to confirm the simulation results.

As can be seen in Figure 18, we have used the results of this study to find the noise levels inside each park, but this has not allowed us to evaluate and compare different open spaces, as the measurements were taken in different months of the year. For this reason, it would not be reasonable to compare parks as, because we are not sure whether the data were taken in the period with or without leaves, it is impossible to obtain any reliable results for the absorption of noise pollution by vegetation.

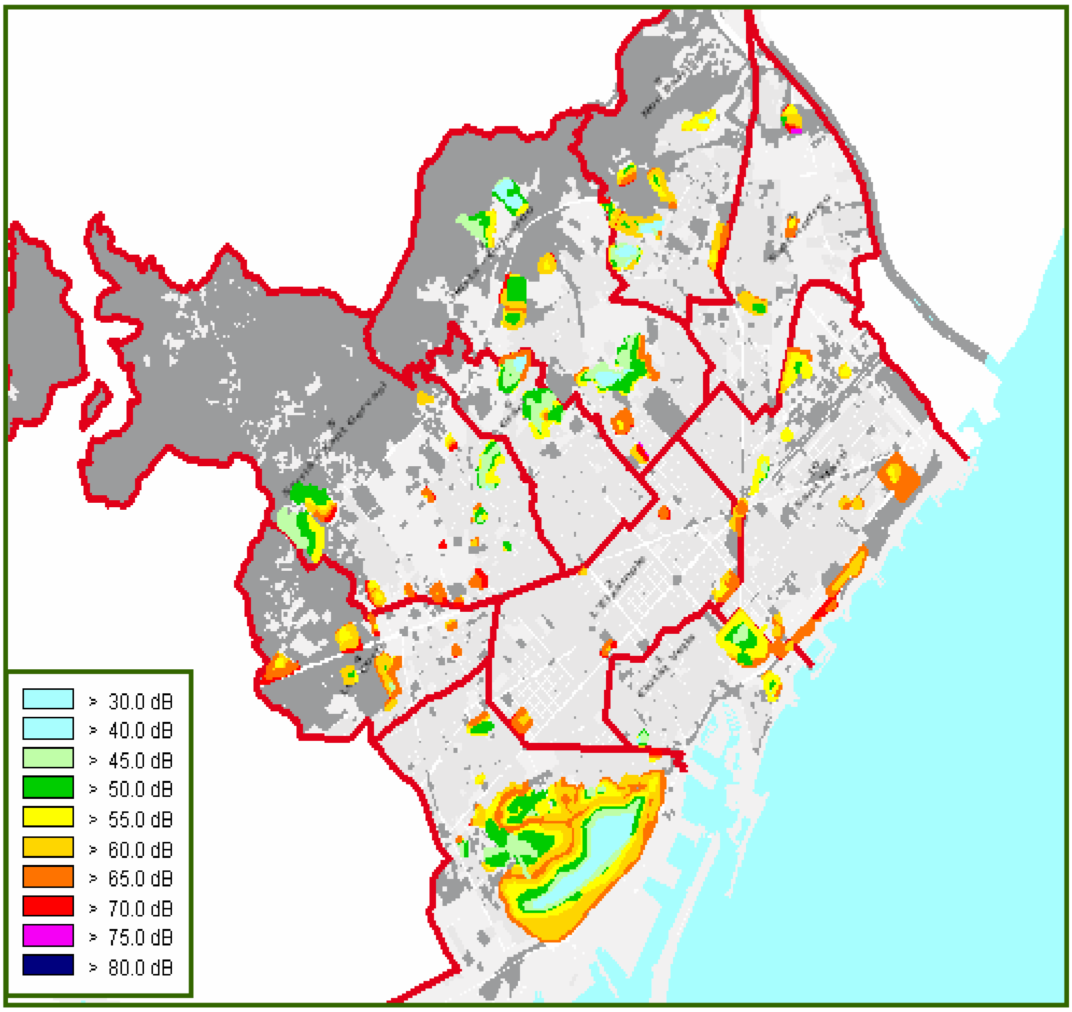


Figure 18. Noise map of Barcelona's parks during the day.

Source: Barcelona City Council.

In any case, the report drawn up by Barcelona City Council shows that Barcelona's parks and gardens have different noise levels compared to the streets, as they are not normally areas that generate noise (except in specific situations or areas). Instead they are receivers of the noise generated in neighboring areas (normally by traffic).

The noise level in parks largely depends on the traffic around them and the size of the park, because the smaller parks and gardens are the ones that have the highest levels, as there is little attenuation due to distance, while the lowest levels are in the larger parks. Montjuïc should be highlighted, as 10% of its territory has levels lower than 45dB in the daytime and 18% at night, according to the Barcelona City Council report (Evaluation of noise levels in the city's parks and garden due to traffic, 2007). In addition, as the distance from the source of the noise increased, the noise level decreases, so that the interior of parks is more peaceful than the edges near busy roads.

But it is not only distance that plays an important role in noise reduction; land relief and tree density are also factors. In any case, there are still many pending debates and much research to be done on the subject of noise, both in Spain and abroad, to clarify concepts.

Trees and the water cycle

There are rainwater drainage models, such as UFORE-Hydro, CITYgreen and others (not applied in drawing up this report), which calculate, based on various data such as rainfall, permeability, ground cover, gradient, etc., the volume of rainwater retained by each tree.

As for the quantity of water intercepted, the different models used have quantified that:

- In Oakland, the tree cover in the city intercepts up to 409m^3 of rainwater a year (USDA Forest Service 2002);
- In Sacramento it has been found that the trees in urbanized areas intercept 2% a year because of winter rains and the large number of deciduous trees. But, in the areas with greatest amounts of Urban forest, the trees intercepted between 6 and 13% - values similar to those found in natural woodland (McPherson et al. 2000);
- Other studies indicate that an urban woodland with 10,000 trees, can retain, on average, approximately 104,000l (104m^3) of rainwater a year (ICLEI 2006);
- In Santa Monica, the studies carried out have shown that the 29,000 urban trees (including street trees) intercept 193,000 m^3 (6.6 m^3/tree) of rainwater a year, equivalents to 1.6% of the total rainfall (Xiao & McPherson 2003);
- Also in Santa Monica, this interception varied from 15.3% (0.8m^3), for a small *Jacaranda mimosifolia* (3.5cm D.B.H), up to 66.5% (20.8m^3), for a mature *Lophostemon confertus* (38.1cm D.B.H.) (Xiao & McPherson 2003). In addition, the study found that the greater the trunk diameter (but not necessarily the height)

the more rainwater intercepted, and that this is also greater in evergreens than deciduous trees, as summarized in Table 14.

Note: *interception corresponds to rainwater retained on plant surfaces (leaves, branches, and the bark of the trunk) and evaporating without reaching the soil.*

As for rainwater run-off (causing soil erosion, sediment contamination and possible flooding), different models indicate that:

- In Modesto it has been calculated that each tree can reduce rainwater run-off by up to 3.2m^3 a year, and this benefit has been valued at €4.56 per tree (McPherson et al. 1999b);
- According to other studies, for each 5% increase in forest area, rainwater drainage is reduced by 2% (ICLEI 2006).

Broadleaved evergreen trees, such as *Magnolia grandiflora*, are the ones that intercept most water. They are followed by conifers, such as *Pinus pinea*, and broadleaved deciduous trees, such as *Platanus x acerifolia*. Large, adult trees provide the greatest benefit, as they have the largest area for retaining water. But, in autumn or winter rains, (when deciduous trees are without leaves) evergreen trees and conifers play a very important role in intercepting water.

Table 14. Rainwater intercepted per tree (m^3/year) according to DBH.

		DBH (cm)					
Scientific name	Type	0–15.2	15.2–30.5	30.5–45.7	45.7–61.0	61.0–76.2	>76.2
Platanus x acerifolia	Large deciduous	1.24	6.46	12.82	19.62	25.99	31.4
Liquidambar styraciflua	Medium deciduous	0.81	2.98	4.77	6.35	7.77	7.77
Jacaranda mimosifolia	Small deciduous	0.83	4.17	7.86	11.12	14.2	17.12
Eucaliptus ficifolia	Large evergreen	0.61	2.97	5.81	9.84	15.03	20.79
Cinnamomum camphora	Medium evergreen	1.08	4.57	8.85	13.81	20.61	20.61
Prunus caroliniana	Small evergreen	0.93	3.33	5.91	9.08	12.79	16.82

Source: Xiao & McPherson (2003) adapted and amended for this report.

DISCUSSION

Urban forest structure

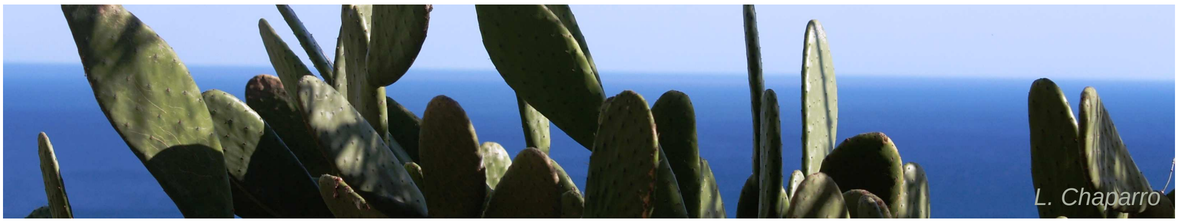
The data collected in drawing up this study on the vegetation in Barcelona comes from a stratified random sample of 579 plots randomly distributed among the different land uses in the city. The results obtained in these plots, which amounted to a total of 23ha sampled, have been extrapolated to the 10,121ha, making up the total area of the municipality of Barcelona.

Urban trees cover 25.20% of the entire study area and there are 1,419,823 trees (approximately 14% of these are street ones). *Platanus x acerifolia*, *Pinus halepensis* and *Quercus ilex* are the dominant species as they represent 49.2% of all trees, 50.6% of the tree leaf area and 43.1% of the total tree biomass. If there was a disease, parasite or pathogen or any other process negatively affecting one of these species, Barcelona's vegetation would be seriously affected. We can therefore consider this situation as a weakness of the system. The planes present infections and both the Plane and the Holm oak are species considered to be vulnerable to an increase in temperatures and more frequent droughts.

The most common tree in the urbanized areas of the city, that is, in the categories Multifamily residential, Intensively used area without buildings and Transport, is *Platanus x acerifolia*. Its population is largely made up of trees of between 15.3 and 38.1cm in diameter, a value higher than the average, which is between 7.7 and 15.2cm.

Overall, Barcelona's trees are quite young (70.7% of the individuals are less than 23cm in diameter) and these young trees are made up of 122 different species out of the 148 tree species existing in the territory as a whole. This fact will not only provide us with a greater diversity of mature trees in the future, as it is currently the young trees that increase the Shannon-Wiener index (3.27, a value that can be considered high), it will also increase the city's tree cover. The weakness indicated in the previous paragraph is therefore on the way to being resolved, if the current process is encouraged and dead or sick trees are replaced following the right criteria.

However, as has been seen in the results, the Urban forest land use, Multifamily residential and Intensively used area without buildings are the ones showing more exotic species, among which some are naturalized while others appear as invaders: that is they have reproductive descendents which are often very numerous and can come to compete with and displace native fauna. These species include *Acacia dealbata*, *Elaeagnus angustifolia*, *Eriobotrya japonica*, *Eucalyptus camaldulensis*, *Eucalyptus globulus*, *Gleditsia triacanthos, Parkinsonia aculeata*, *Schinus molle* and *Ulex parviflorus,* as well as *Ailanthus altissima*, *Opuntia ficus-indica* and *Robinia pseudoacacia*, the latter catalogued according to DAISIE within the 18 most invasive terrestrial plant species in Europe.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But to speak of invasive species in parks and gardens in the city is not very relevant, as this problem is important only in natural areas, where the study has identified 5.6% of individuals corresponding to invasive species (approximately 44,000 individuals as well as others likely to be invasive in the not very distant future). Gardens clearly show a large number of exotic species, and, although this is not always the case, it is common for cities to be the gateways for invasive species that can have devastating effects on local biodiversity. And it is on this point that special care must be taken and invasive species must be prevented, as far as possible, from spreading through natural areas. It is perfectly acceptable to use exotic species in gardening, but this must be done prudently, avoiding species with a risk of expansion outside urban limits.

The great part of Barcelona's area is formed by impervious material (64%), like asphalt, cement, rock and others, while the remaining 36% is largely occupied by woody vegetation, herbaceous areas, grass and a small proportion of ponds or artificial lakes.

The proportion of impermeable material would be much greater had this report not included the area of Collserola, which occupied an area of 1,795 ha. The space available for planting is only 3.6% of the total area. However, despite the little available permeable space remaining in the city, this figure would correspond to more than 200,000 new trees which could come to be planted in Barcelona; that is, double the number of street trees we currently have. Even taking for granted that part of this available permeable space already has uses that cannot be altered, the fact is that there is still room for a considerable increase in tree cover.

Land uses where more trees could be planted are: Urban forest (particularly in places where there is grass, although these often need to be kept as they are); Intensively Used Areas Without Buildings (due to the fact that in this category, apart from the pedestrianized areas where there are empty planters, there are also areas without buildings or in transformation, often with herbaceous ground cover) and, finally, Natural forest (where there are areas with little shrub or tree cover and where new individuals could be planted). However, the management of natural space has different characteristics and agents.

So, Barcelona’s urban vegetation could be increased, but if we compare it with other cities where the same UFORE model has been used, Barcelona’s tree cover is already quite considerable: 25.2% in comparison with 21.2% in Boston or 21% in Oakland – cities with numbers of trees similar to Barcelona (1,183,000 and 1,590,000 respectively). Tree density in Barcelona is slightly higher, at 141 trees/ha, than in Boston and Oakland, with 83 and 120 trees/ha respectively. However, these results obtained in Barcelona, which seem high, would be much lower had this study not included the part of the Collserola range belonging to the municipality, as has already been mentioned. So, if we extract the values obtained in the Natural forest category for the Collserola range from the total result, Barcelona’s tree cover would become 15% and the density 78 trees/ha, values closer to those in compact cities like San Francisco, with 12% cover and 55 trees/ha or Chicago, with 11% cover and 68 trees/ha.

Another possibility for encouraging vegetation, still very little used in Barcelona but with which there is a great deal of experience in other cities, consists of the creation of plant walls and façades, dividing walls and green terraces. By promoting this kind of vegetation we would achieve a greater plant presence inside the densest urban areas. The blue building at the Fòrum, the future National Museum of Natural Sciences, will be an interesting experiment in this sense. There are companies that can offer solutions which, naturally, must be adapted to Barcelona's specific conditions in terms of the balance of water, salinity in coastal zones, etc.

This type of construction would not only make the city more beautiful, it would also take an active part in providing direct benefits such as prolonging the live of the roof; acting as a sound barrier; improving the building's heating and air conditioning – reducing heat loss and energy consumption in winter but also reducing the head island effect, reducing temperatures in the city and, consequently, the energy cost deriving from this and offering leisure opportunities (growing fruit, vegetables, flowers...). As well as these benefits, they would offer us other very important environmental services, such as filtering pollutants, reducing the risk of flooding in the city, thanks to the interception of water by the plant cover, and providing more habitats and consequently more biodiversity, etc.

There are technical difficulties. The most important is that, in a country with long droughts, maintenance cannot always only be carried out with rainwater. An appropriate choice of species will have to be accompanied by structures making it possible to use rainwater as far as possible, and, in some cases, channeled non-drinking water.

Creating green corridors greenbelts, linking the urban forest in the city with peri-urban natural areas, as well as increasing areas inside blocks by creating community gardens or courtyards freely accessible by the public and with permeable soil (as is happening with the gradual increase in the recovery of the interiors of blocks in the Eixample) and increasing the number of urban vegetable gardens (subject to regulation and consensus among residents) would increase the urban forest. It would make the compact city of Barcelona look more beautiful and offer many social benefits associated with education, as well as health, leisure or the possibility of doing sport, among many other possible services.

These three buildings are good examples of the incorporation of vegetation into the city with the incorporation of vertical gardens on their façades. From left to right, they are the Athenaeum Hotel (London), the Caixa Fórum (Madrid) and the Museé de Quai Branly (Paris).

These three buildings are further examples, incorporating green roofs. They are, from left to right, the roof of the Mountain Equipment Coop. in Toronto (Canada), Chicago City Hall (Chicago) and the Banco Santander (Madrid), which shows the greatest vegetation cover anywhere in Europe.

Gardens show a high level of plant biodiversity as each tree or shrub can, in principle, be different from its neighbor. Despite this, such diversity is non-functional; that is, it is like a museum. Such complexes of plants do not show high levels of interaction and do not, therefore, form true ecosystems. In general, gardens have little value as functional systems in which significant ecological processes can take place. Their main function is a different one, more aesthetic and recreational. However, gardens can offer shelter, food or a staging post to different species of birds, insects or other animals, thereby increasing the animal diversity associated with vegetation.

But Barcelona's parks or urban woodlands are often too small to maintain a varied flora and fauna for themselves. For this reason, increasing urban vegetation would offer a large variety of biotopes and would have a large number of ecological niches that could be occupied by many different species, thereby increasing biological diversity. But, in order to have a great diversity of plants and species in the city, the connections between the urban forest inside Barcelona and the ecosystems surrounding the city should not be interrupted. This is why, as has already been said, green corridors and belts should be promoted, as well as using the space available for planting which, as has been seen, is 3.6% of the area of Barcelona. The recovery of the interiors of blocks and vegetable gardens and the greening of walls, dividing walls and terraces should also be promoted.

In conclusion, Barcelona has the characteristics of a compact city, with not very dense urban vegetation, similar to other important cities in the world. However, a considerable peripheral area of trees lies within the municipality, which underlines the importance of Collserola Park in the region as a whole, as well as for the opportunities it provides for enjoying nature and conserving biodiversity. This makes it advisable that maximum care should be taken in protecting this exceptional nature reserve lying so close to the urban area. What is proposed here is to increase the vegetation inside the compact city, integrating spaces to make the urban environment and infrastructure – particularly transport routes and block interiors – more permeable to plants and consequently to animals. This would guarantee public access to the enjoyment of vegetation in a less concrete city.

Effect of vegetation on air quality

Healthy trees are efficient in reducing many pollutants. In 2008, the trees and shrubs in Barcelona removed 305.6t (166t of PM10, 72.6t of O_3, 54.6t of NO_2, 6.8t of SO_2 and 5.6t of CO), a service which has a value to society estimated at 1.1 million euros. In other cities with a similar number of trees per hectare as our city, these services are greater than in Barcelona. In Baltimore, for example, the air pollution removal calculated was 430t/year and in Washington 540t/year. The values associated with air pollution removal by trees in these two cities are approximately 1 million and 1.3 million euros respectively. In Minneapolis, with 160 trees/ha, air removal was less than in Barcelona, with 277t/year, which, according to Nowak (2006), is due to the short season when the trees there are in leaf. It is worth mentioning that the trend observed towards extending the vegetation period as a result of climate change means that this environmental service is likely to increase in value, but this will only happen if city vegetation is kept in good condition and, in the Mediterranean region, withstands increased periods of drought.

Comparing the pollution eliminated between cities is always a delicate operation, as rates of elimination by vegetation vary considerably according to the quantity of pollutants present in the atmosphere, the length of the period in leaf and the growth period, the leaf area, the rainfall and other meteorological factors. In this sense, we have found that the standardized pollution removal by Barcelona's trees (9.35g/m^2 of canopy cover/year), is comparable with Brooklyn (10.2g/m^2/year), Chicago (8.9g/m^2/year), or even Atlanta (10.6g/m^2/year).

Continuing the comparison between different cities, Barcelona's trees above all retain PM10, and, in decreasing proportions, O_3, NO_2, SO_2 and CO, while in the American cities to which the same model has been applied, the pollutant most extracted from the air by the vegetation is O_3, followed by PM10. This is due to the fact that Barcelona has higher PM10 emissions compared with other cities, probably due to the high density of traffic in a very compact city.

No data have been obtained on the decontamination caused by the different species found in Barcelona, so we cannot make recommendations from this point of view for altering the composition of the vegetation, but we did want to add the research by the USDA Forest Service (Nowak, 2000c) which shows a list of the best positioned tree species in terms of improving air quality in the United States. This information is based on studying the combined effects on absorption of the different pollutants, VOC emissions and the reduction of air temperature by 242 species of adult trees (in U.S. urban conditions). The trees on the list are tolerant of the pollutant indicated (if they are not, a note has been added). The Total column shows a ranking based on the individual effects of the pollutants weighted with an estimate of the cost of these to society.

Table 15. List of the top-rated tree species for improving air quality in the United States.

Ozone	Carbon monoxide	Total
Ulmus procera	*Tilia americana**	*Ulmus procera**
Tilia europea *[I]	*Fagus grandifolia*	*Tilia europea*
Fagus grandifolia	*Tilia tomentosa**	*Liriodendron tulipifera* *[S]
Betula alleghaniensis	*Ulmus rubra*	*Fagus grandifolia*
Liriodendron tulipifera *[S]	*Fagus sylvatica*	*Tilia platyphyllos**
Tilia americana *	*Betula alleghaniensis*	*Betula alleghaniensis*
Fagus sylvatica	*Tilia euchlora**	*Fagus sylvatica*
Tilia platilphyllos *[S]	*Ulmus procera**	*Tilia americana**
Betula papyrifera	*Ginkgo biliba**	*Ulmus americana*
	Liriodendron tulipifera *	*Ulmus thomas*
Particulate matter	**Sulfur/nitrogen dioxide**	**Total**
Ulmus procera *	*Ulmus procera* *[I/U]	*Tilia cordata**
Platanus x acerifolia *	*Tilia europea* *[T/S]	*Tilia tomentosa**
Cupressocyparis x leylandii	*Populus deltoides* [T]	*Betula papyrifera*
Juglans nigra	*Platanus x acerifolia* *[T]	*Celtis laegivigata* *
Tilia europea	*Liriodendron tulipifera* *[T]	*Fraxinus excelsior* *
Abies alba	*Juglans nigra* [S/U]	*Ulmus crassifolia*
Larix decidua	*Betula alleghaniensis* [S]	*Betula nigra* *
Picea rubens	*Fagus grandifolia*	*Larix decidua*

Source: Nowak, 2000c.

Note: bioclimatic zones and other environmental factors must also be considered.

* = Species, or different cultivars, specially recommended as street trees or for urban conditions. **I**= intermediate tolerance to the pollutant; **S**= Sensitive to pollution; **T**= tolerant of SO_2, unknown for NO_2; **I/U**= intermediate tolerance of SO_2, unknown for **S/U**= Sensitive to SO_2, unknown for NO_2 and, finally, **T/S**= Tolerant of SO_2 and sensitive to NO_2.

As has already been mentioned making recommendations from this point of view is a very delicate matter because of the lack of specific information for the city of Barcelona. However, it can be stated that a good strategy for increasing air purification by vegetation is to increase plant cover and leaf area by, for example, planting shrubs under tree crowns. In areas with high emissions at ground level (for example on urban roads) the plant cover should be positioned along the street or road but not covering it, thereby allowing the pollutants to disperse upwards and increase their elimination by the adjacent trees. In areas with high population densities, such as in the Multifamily residential category, or where there is a high concentration of pollutants, the increase in appropriate plant cover could considerably improve human health and well-being.

Effect of vegetation on biogenic emissions

As well as improving air quality in cities, urban vegetation helps to reduce the air temperature in the summer, cut energy consumption in homes and, therefore, also reduce carbon emissions derived from this. But there is another factor that can negatively affect air quality – the formation of VOCs and, consequently, also O_3 and CO.

During 2008, Barcelona's trees and shrubs emitted 184t of VOCs (95.4t of isoprene, 36.1t monoterpenes and 52.6t of other VOCs), 32t of CO and 304t of O_3. By comparison, the vegetation in Brooklyn produced, in a year, 96.6t of VOCs (49.9t of isoprene, 13.9t of monoterpenes and 32.8t of other VOCs), approximately half the figure for Barcelona. Unfortunately, in this case it has only been possible to make the comparison with the values obtained in Brooklyn which, apart from having a different species composition and many other factors and characteristics different from those of Barcelona, has only 610,000 trees, around half of the number in Barcelona.

In Barcelona, the genera that participate most in forming O_3, and which it would therefore be advisable, from this point of view, to reduce in the compact centre of the city, are the genera:

> *Quercus*, *Platanus*, *Robinia*, *Populus*, *Rhamnus*, *Casuarina*, *Pinus*, *Eucalyptus*, *Phoenix*, *Pistacia* and *Salix*, among others, making up 59% of the total leaf biomass.

By contrast, the genera that have a negative value for O_3 production – that is, which eliminate it from the atmosphere – are:

> *Pyrus*, *Tilia*, *Catalpa*, *Fraxinus*, *Tamarix*, *Ligustrum*, *Ulmus*, *Melia*, *Prunus*, *Celtis* and *Cupressus*, and up to 32 more genera. The total number of individuals that eliminate O_3 represents only 41% of the total biomass, but, by contrast, 60% of the genera existing in Barcelona.

These results are also comparable with those for Brooklyn. However, it must be admitted that, due to the great degree of uncertainty over atmospheric modeling, the complexity and variations in conditions in each city studied with the UFORE model, the results obtained for VOC and consequently O_3, formation by vegetation in the cities where this model has been applied, the value of the comparisons is relative.

It must also be remembered that VOCs are not pollutants if the atmosphere is clean, as a change in concentration of a pollutant of 1ppm when their concentrations in the atmosphere are low is less significant than an increase of 1ppm when concentrations are near the European Commission's standard levels (as at this level pollutants have a greater impact on human health). If the air of a zone does not show a polluted atmosphere or if the values are low, VOC production will have no negative effects on air quality or on people's health. In cities with more polluted air, the presence of plant species participating in the formation of VOCs and in the formation of O_3 will have a relatively greater effect on air quality and people's health.

As VOC emissions depend on the temperature and trees generally reduce this, an increase in tree cover reduces overall VOC emissions and therefore reduces O_3 levels in urban areas (Nowak et al. 2002). But, as Taha (1996) shows in a study carried out on the south coast of California, an increase in tree cover results in a reduction in O_3 when the trees planted emit few VOCs. So, a good strategy for helping to reduce ozone levels in cities is to increase vegetation, particularly species that emit less VOC.

This study has not included the herbaceous layer or grass, but in Kirstin (Australia) it has been found that grass, and mown grass, are important sources of VOC emissions and it has been estimated that 1/3 of photo-chemically reactive VOCs in an urban environment come from grass and its waste after mowing.

We have said that changing the composition of the genera that generate most VOCs, such as *Eucalyptus*, *Casuarina*, *Robinia*, *Populus*, *Platanus*, *Quercus*, *Salix* and *Pistacia*, could be a strategy to reduce these polluting emissions generated by the vegetation itself. In any case, Nowak (2000) points out that if we have species that generate high proportions of VOCs, we must not deduce that urban vegetation is a producer of pollutant but rather that it is more appropriate to say that the maximum vegetation purification potential has not been achieved.

Some of these species that are not advisable due to the production of VOCs offer us other environmental benefits we should not forget, such as retention of particulate material (PM10) that is shown as one of the most important pollutants in the Barcelona area. So, according to this last parameter, species of the following genera would be recommendable as street trees: *Platanus* (deciduous with great capacity to retain airborne particles and adapted to urban conditions) as well as *Ulmus*, *Juglans* and *Tilia*, but also *Celtis* and *Fraxinus*, among other possible genera, taking into account their sensitivity to urban conditions and to the site to be planted.

More studies will be necessary of the effects the different species have on pollution, particularly those that foster the formation of O_3. When it comes to choosing species appropriate for Barcelona, many other factors must be taken into account, including life expectancy, maintenance, differences in behavior concerning transpiration and contribution to cooling the air and vulnerability to pests or climate change.

According to Peñuelas and Llusià (2003), as VOC emissions respond to temperature, the global warming of the last 30 years could have increased them by about 10% and the subsequent increase of 2-3ºC in the average global temperature forecast for this century could increase VOC emissions by another 30-45%. Despite the fact that, according to these authors, there is an important gap in accurate, complete knowledge of the effects of these compounds on global change, everything seems to indicate that the greatest effect of environmental change will be an increase in VOC emissions. As emissions are very variable in space and time and between different species, it is necessary to continue interdisciplinary research on different scales and to improve the simulation models used for calculating this environmental service.

Effect on greenhouse gases

The vegetation in Barcelona and its management can affect the local climate, due to the modification of the urban atmosphere and the chemical emissions generated. It has been estimated that in 2008 carbon storage in Barcelona was 113,437t (11.2t/ha). This level of storage is very similar to that of Oakland (11t/ha), but less than the value estimated for Boston (20.3t/ha), where the trees are larger.

Carbon storage by Barcelona's vegetation is equivalent to the quantity of carbon emitted by the city's population in **28.5 days** (calculated based on C emissions per inhabitant in 2008, Barcelona statistical yearbook). The total carbon sequestered by the trees, which take years to sequester it, is equivalent to the emissions generated by 6,000 inhabitants of Barcelona during one year (equivalent to 0.8% of the population).

Gross carbon sequestration estimated for Barcelona is 6,187t/year, less than the figures found for other cities but, concerning gross carbon sequestration per hectare (0.6t/ha/year), the value for Barcelona is very close to those for the American cities where the same model has been applied, such as, for example, Boston: 9,500t/year (0.61t/ha/year); Syracuse: 4,700t/year (0.73t/ha/year); or Chicago: where gross carbon sequestration is very high, 40,100t/year, as it is a very big city, but if we take into account the area the result is quite similar to that for the other cities (0.67t/ha/year).

In Barcelona, the net carbon sequestered every year (gross carbon minus emissions due to decomposition), was 5,422t/year (0.54t/year/ha), very similar to the results found in the cities of Boston, with 6,900t/year (0.49t/year/ha), and Syracuse, with 3,500t/year of net carbon sequestered (0.54t/year/ha).

However, as has already been mentioned, if the part of the municipality corresponding to the Collserola range had not been included in this study, the differences between the cities we are comparing here would be marked, and we would find that the carbon stored in Barcelona would be approximately 71,329t (7.05t/ha), the gross carbon sequestered would have an estimated value of 3,742t/year (0.37t/year/ha) and the net carbon sequestered would be 3,323t/year (0.33t/year/ha), lower results than any other city analyzed with the UFORE model. This is understandable if we consider the more compact nature of the Mediterranean city compared to the American ones and it once more emphasizes the importance of the forest area of Collserola in the Barcelona ecosystem.

The man factors increasing carbon storage and gross sequestration per hectare are tree density and the increase in the proportion of big trees with large diameters. Large trees, with a healthy leaf area, increase C sequestration and the air purification rate. Trees in Barcelona with a diameter of more than 83cm sequester up to 31 times more C than trees smaller than 8cm in diameter. As we have seen that, in Barcelona, the predominant tree size is small, the future growth of the trees will improve the situation. Apart from this, the species with a relatively long life expectancy will have a positive total effect on CO_2, as the tree death, and therefore replacement, will occur less frequently.

The majority of net C sequestered by a woodland is due to the carbon sequestration by the first generation of trees, as in an old woodland with little regeneration, decomposition can be greater than production and even generate a net release of C. The C stored therefore forms part of a cycle over time depending on the rising and declining population. When the woodland grows, carbon accumulation is greater than decomposition and carbon storage increases. This storage can increase over a long period of time (according to some authors up to 20 years or more) if timber products derived from dead trees are recycled and turned into benches, containers or other types of furniture. On the other hand, if the timber products are transformed into compost, burned or shredded, the carbon sequestered is quickly released into the atmosphere. So, it must be taken into account that, due to decomposition, almost all the C sequestered can come to be turned into CO_2, and the possibility of having trees whose timber can be recycled, such as walnut, should be considered. Pruning waste from other trees, such as *Fraxinus* (or even *Platanus*) could be used to make craft products, for example.

Urban vegetation affects emissions or the formation of greenhouse gases due to the emission of certain gases by the plants themselves, as we have already mentioned, but also due to the emission of other gases linked to maintenance, such as those from vehicles, chainsaws and excavators. All of these contribute to the formation of O_3 and CO.

It must therefore be borne in mind that, if maintenance work on a woodland or urban forest is carried out with machines using fossil fuels, the benefits will be reduced due to the CO_2 emissions resulting from this maintenance. The combustion of petrol or diesel oil, for example, emits carbon dioxide but also volatile organic compounds, carbon monoxide, nitrogen and sulphur oxides, as well as particulate material (Graham et al. 1992). If urban vegetation is maintained consuming these types of energy, urban woodland may become a source of carbon. In summary, a sustainable urban vegetation strategy should reduce emissions deriving from maintenance as far as possible and should therefore plant trees requiring little maintenance, with a long life expectancy, whose wood can be recycled once they are dead.

Continuing with the example from the previous section concerning grass (not looked at in this study), another study, carried out by the University of California, –Irvine (UCI, 2010)– has shown that grassy areas eliminate carbon dioxide from the atmosphere through photosynthesis and store it in the form of organic carbon in the soil, so they are important carbon sinks. However, due to the production of greenhouse gases from the fertilizers used, mowing and other maintenance practices, the release of carbon by ornamental lawns in parks is 4 times greater than the carbon stored. In addition, these emissions include nitrous oxide, one of the most problematic greenhouse gases in the warming of the earth.


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Effect on energy consumption

Trees can also reduce energy consumption in homes and therefore reduce C emissions generated by power stations. But this does not always occur, as a tree planted in an inappropriate place can increase the energy use needed to heat or cool a home.

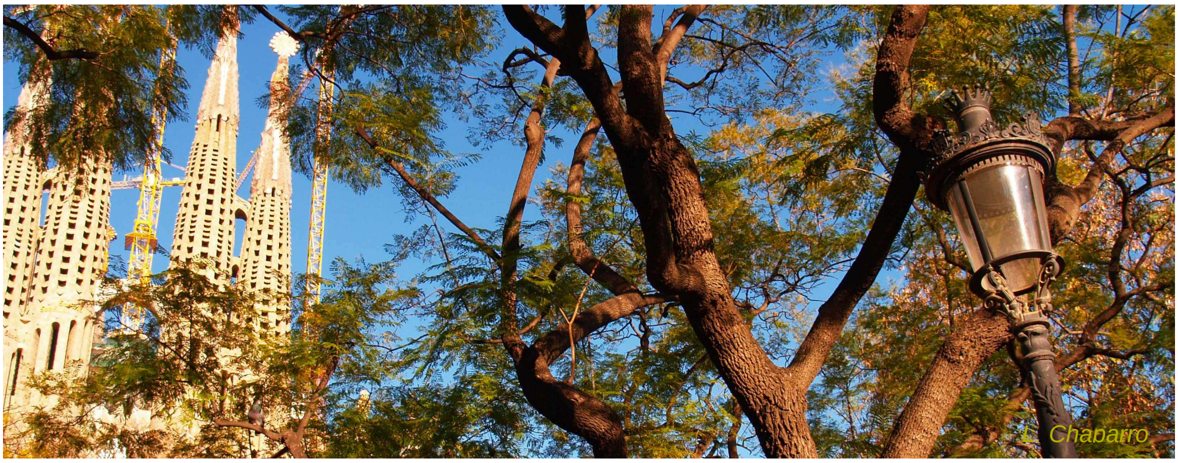
The reduction in temperature offered by the shadow of certain trees, such as *Broussonetia papyrifera*, *Morus alba*, *Celtis australis* and *Platanus spp.* during the summer should be highlighted and this can come to moderate energy consumption deriving from the use of air conditioning. Meanwhile others, like *Albizia julibrissin*, *Prunus cerasifera*, *Populus spp*. and *Catalpa bignonioides*, offer a low level of temperature reduction.

However, it should be stressed that, as has already been mentioned, the results given by the American UFORE model were not based on the true Mediterranean climate. In addition, unlike American cities, the number of air conditioning machines in Barcelona has still not stabilized and continues to grow. It is therefore important to analyze the figures relating to electricity and to repeat the simulation carried out in this section once the UFORE model is capable of analyzing the energy saving from trees in cities outside the United States.

The comparison with other cities where the same model has been applied is difficult, as, apart from the climatology, type of city, trees, or other differences such as energy costs, the majority of reports consulted lack detailed information on the energy issue. However, by way of example, in Milwaukee (Wisconsin), a city with a damp continental climate, with half Barcelona's number of inhabitants, UFORE has calculated a heating cost in winter of 5,000Mwhs and 8,400 euros and a saving on cooling during the summer of 11,800Mwhs and 1.4 million euros, with the overall positive result being a saving of 6,800Mwhs and 1.2 million euros a year.

In Washington, with a population 4 times greater than Barcelona and a marine continental climate, the vegetation has not brought economic costs but rather benefits, particularly in the summer, with an overall saving of 25,500Mwhs or 3.7 million euros a year.

So, it is important to foster the shade effect of trees, not only to achieve greater economic benefits and shade in summer (as a more marked increase in temperatures is forecast in the summer (4.1ºC) than in winter (2.6ºC), but also to promote the cooling deriving from transpiration and thereby reduce temperatures and temperature-dependent VOC emissions. Because of this, species with a relatively high leaf areas and transpiration rates should be selected, as well as choosing good locations for trees with respect to housing. The height, transpiration, leaf and branch density also influence energy use in homes (McPherson 1994). However, promoting transpiration involves greater water consumption and would only be possible if there were surpluses that could increasingly be applied for watering.



On one hand, climate change trends make this difficult as they threaten the survival of precisely the plants that transpire a great deal; on the other, groundwater flows are increasingly being recovered in Barcelona, but it is difficult to return to the old systems of individual watering of street trees. Only systems channeling rainwater and surplus groundwater to the planters can help in alleviating the possible problems associated with drought and improve the climatic effect of trees.

Finally, our conclusion is that the participation of urban vegetation in the energy metabolism of the city is not very significant in comparison with this energy metabolism as a whole, dominated by flows related to human activity. But we must realize that the role of vegetation in the city's energy metabolism is, while perhaps not significant at global level, much more important on a smaller scale or even in a microclimate scale. An increase in urban trees would undoubtedly increase the participation of vegetation in Barcelona's energy metabolism.

Effect on noise reduction

The Barcelona Noise Map (2006), including information on noise in parks and gardens, shows that open spaces do not generate noise (except in specific situations or areas) but rather receive noise generated in neighboring areas (normally traffic) and that, as we go into a park, the noise is attenuated due to the distance. Large parks and gardens are therefore usually the areas with least noise pollution.

Apart from distance, many authors agree that the land relief and tree density play a very important role in noise attenuation. In any case, despite the large quantity of research on sound propagation through trees, it is necessary to go into much greater depth and clarify concepts, as the methodology used has been different in many of the articles we have reviewed and the data is often contradictory. Despite this, we can summarize that:

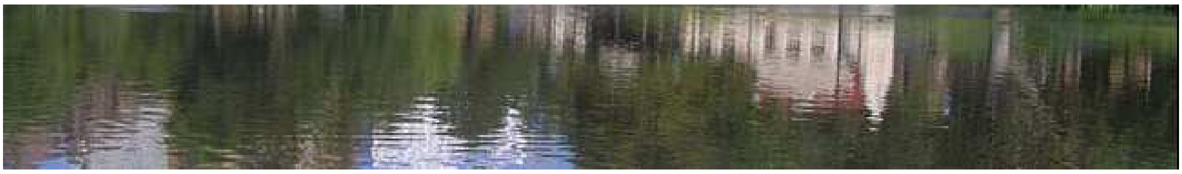
1. Trees (generally deciduous ones), with broad, leathery leaves and dense foliage, are better than conifers at reducing noise.
2. Reduction is greater when the tree coverage is combined with a high density of shrubs and other plants. So it would be appropriate to promote a diversity of species with dense foliage and of different shapes and heights.

Generally, it seems that a mixture made up of deciduous trees and conifers, together with shrubs, could be the most efficient in attenuating noise (Bucur 2005). In any case, the effect of trees is modest in this sense, and only in the case of parks of a certain size can effective management measures be taken. Plant cover on façades and terraces can contribute if the openings are appropriately designed, with double glazing and good insulation.

Trees and the water cycle

As a result of extensive urban development, the large quantity of smooth and asphalted covers alters the surface drainage of water in cities, where up to 90% of rainwater can be lost (Higueras 2006). By contrast, in areas with vegetation, only 5-15% of water is lost through run-off, and the rest evaporates (5-20%), soaks into the soil (Bolund and Hunhammar 1999) or is stored in the branches and leaves of trees. Trees, as well as reducing the volume of run-off water, also help to remove the pollutants present in the soil, largely originating from wheeled traffic, reducing the risk of flooding and water pollution.

According to the study by Xiao and McPherson (2003), 29,299 urban trees (including street trees), intercept up to 193,168m^3 (6.6m^3/tree) of rainwater a year. These figures prove the importance of water retention by trees, whose importance will depend on the species, the trunk diameter, the architecture of the tree, the climate (temperature, relative humidity, net solar radiation and wind speed) and, finally, the intensity and duration of the rain (USDA Forest Service 2002).



So, apart from increasing the permeable surface of Barcelona (which, as has been seen, is only 36%) and the tree cover, and improving tree health, a possible solution for making use of rainwater in the city could be to reuse urban rainwater in open spaces as an economical means of treating and removing pollutants, promoting tree growth, making them less vulnerable to drought and improving the benefits they bring in terms of the climate and eliminating pollutants. Nowadays, the water supply sources for the city of Barcelona are largely of surface origin (Rivers Ter and Llobregat), although in the last few years the presence of resources derived from groundwater have increased significantly.

What we suggest here is the creation of bioretention areas – that is, areas with vegetation designed to intercept storm water (extremely important for reducing run-off in urban areas). Rainwater can be directed to the bioretention areas, which would act as pollution filters as well as retaining the water. Well-designed bioretention areas can trap and retain up to 99% of pollutants, as demonstrated by a study carried out in Maryland (United States), where it was shown that well-designed bioretention zones were capable of eliminating from rainwater around 95% of copper, 98% of phosphorous, 20% of nitrogen and 20% of calcium. In addition, this same water could subsequently be reused, for example, to water parks, gardens and street trees, clean streets, etc.

RECOMMENDATIONS DERIVING FROM ENVIRONMENTAL SERVICES

The options mentioned below could help to improve air quality in Barcelona, as well as increasing carbon sequestration and storage and reducing rainwater run-off in urban areas:

1. Maintain tree plant cover in order to maintain the C currently stored by the urban vegetation and the levels of pollutants absorbed;
2. Expand it, to still further increase the pollution eliminated, C sequestration and storage and, consequently, the rainwater intercepted;
3. Water trees and shrubs appropriately, which would increase the pollution extracted by the vegetation and tree growth, and therefore C storage, even further;
4. Recycle the timber from pruning or from dead trees, to increase the time the C is stored in the wood;
5. Minimize the use of fossil fuels in the city and in the maintenance of urban vegetation to reduce pollution emissions;
6. Plant species that produce timber that is easy to recycle, that require little maintenance, that have long life spans, that grow averagely quickly or quickly, that are large when mature and that are adapted to the conditions of the site, so as to reduce pollution emissions deriving from maintenance activities themselves[*];
7. Improve the state of health of trees and C sequestration by replacing dead trees with young, healthy ones, particularly in land uses emitting CO_2 (industrial or commercial, transport, Multifamily residential...);
8. Plant pollution-resistant trees in the areas with worst air quality to maximize air purification and the health of the people who live in those areas;
9. Plant evergreen species to reduce levels of particulate material throughout the year;
10. Maximize the use of species emitting few VOCs to reduce the formation of O_3 and CO;
11. When water is available, plant species with high leaf areas and transpiration rates, to promote transpiration and the cooling of the environment in the summer and to reduce the temperature of the vegetation and therefore its VOC emissions.

12. Plant new deciduous trees, correctly oriented, around buildings to promote energy conservation in homes and thereby reduce the C emissions associated with the production of the electricity consumed;
13. Plant trees (preferably evergreen ones) with broad, leathery leaves and dense foliage, with a high density of shrubs, conifers and other plants, in order to absorb noise pollution;
14. Increase the permeable area immediately under the tree to increase rainwater soak-away and reduce run-off;
15. Create bioretention areas to reduce run-off in urban areas, and for purifying, storing and reusing rainwater.

** Some characteristics may be difficult to achieve. In general, long-lived trees grow slowly. Evergreen and deciduous trees have advantages and disadvantages depending on the places where they are planted. Appropriate selection will have to take many criteria into account and optimize them, depending on the site.*

VULNERABILITIES OF URBAN VEGETATION

Until very recently, the trend was to count carbon storage and sequestration by the vegetation without taking into account, or rather, forgetting, the emission of greenhouse gases due to maintenance – a serious error. For this reason, it is necessary to continue research, not only into the environmental services generated by the urban forest, but along the lines of eco-physiological studies making it possible to give us a selection of species adapted to the forecast environmental conditions, as well as the resistance to pests, pollutants, drought, growth speed and VOC emission factor of each variety, in order to evaluate which species offer the least maintenance requirements and, therefore, the greatest environmental benefits, while at the same time trying to find a design for maintenance actions, such as pruning, watering and machinery use, that reduce emissions.

However, for Catalonia, according to the various scenarios and models used, as has been mentioned in the introduction on greenhouse gases, for the end of the century an average increase in temperature of 3.5ºC can be expected, with a more marked increase in summer than in winter (4.1ºC and 2.6ºC respectively GIECC 2007, although some models give higher values, of up to 6-7ºC, for summer maximums). Also, as announced in various scenarios, this increase in temperatures will probably be accompanied by a reduction in rainfall of between 5% and 20% according to Moreno (2005), or rather, rainfall will become more irregular. Almost all the models indicate that the Mediterranean area will be one of the regions in the world most affected by climate change. If it is as forecast, droughts will appear more frequently and more intensively than in recent years, the climate will turn drier, affecting natural vegetation and crops as well as the quality and availability of water.

So, we also wanted to include in this report a small section on the vulnerabilities of the urban vegetation and to look at making proposals to mitigate climate change. It is clear that, if the changes occur slowly, many species will also be displaced slowly, but if the change is sharp some will disappear, as they will not have time to migrate before the conditions cease to be favorable. Competition between plants, interactions with animals and microbes and, in general, the climatic impact on the structure and function of woodland will be important, as well as the predictable increase in forest fires in the natural vegetation, but we cannot predict what it will be like. However, in the case of urban vegetation these changes may be mitigated thanks to human action, which is, at the same time, the main cause of the changes themselves.


L. Chaparro

Vulnerability and general recommendations

According to the experts, there will be a reduction in rainfall. So, if there is a lack of water – with the increase in evapotranspiration with the temperatures and possible reduction in rainfall – carbon sequestration and storage will be lower, as tree growth will be affected:

1. But, if water is administered, productivity could increase, if the vegetation does not reach its maximum capacity and acclimatizes to the increase in CO_2 (although further studies are required on this very complex aspect, as the different species show different behavior);
2. Generally, vegetation is much more sensitive to the quantity of water available than to temperatures; that is, temperature variations do not necessarily have dramatic consequences for vegetation (at least within the limits of a few degrees) while changes in rainfall can have rapid effects. It is therefore extremely necessary to plant trees with low water requirements in areas where watering is not applied;
3. Creating bioretention areas would make it possible to have large additional quantities of rainwater available for watering.

49.2% of all the trees in Barcelona belong to the species *Platanus x acerifolia*, *Pinus halepensis* and *Quercus ilex*. If there was a disease, parasite or pathogen that negatively affected one of these species, Barcelona's vegetation would be seriously affected. This fact, added to the possible lack of water, means that the plant would go into physiological stress, making it vulnerable to various devastating pathologies: fungi and pests, such as borers, worms and leaf-strippers. In addition, both the plane and the cork oak are species considered vulnerable to an increase in temperatures and to more frequent droughts:

4. So, it is necessary to increase the tree diversity of Barcelona, prioritizing species from bioclimatically suitable zones resistant to Barcelona's frost profile, as the risk of late frost is unlikely to change;
5. Manage urban forest and maintain irregular, mixed woodland, as monodominants offer greater propagation risks;
6. If necessary, alter the species composition to reduce their vulnerability to future disturbances, always controlling the entry of non-native species.

Warming and droughts will increase losses, particularly in young trees and mature trees in urban environments, leading to high costs in maintenance and providing new replacement plants:

7. For this reason, it is necessary to select drought-resistant species, possibly from the continental Mediterranean climate, which are well adapted to the climatic conditions of the city. As has already been mentioned, they should also require little maintenance, have a long life spans, if possible grow quickly (although this will reduce the quality of the timber and its possible reuse) and be large when mature, thereby reducing pollution emissions deriving from maintenance activities.

According to Peñuelas and Lluisà (2003), an increase of 2-3ºC in the overall average temperature could increase VOC emissions by a further 30-45%, which would cause a considerable increase in tropospheric ozone concentrations, and therefore an added health risk:

8. As VOCs are formed in polluted atmospheres, the most obvious recommendation would be to reduce the level of pollutants in urban centers as far as possible, as has been indicated in the air quality section. In Barcelona alone, it is estimated that pollution is the main or indirect cause of 3,500 deaths a year;
9. As well as promoting plant species that emit fewer VOCs, such as *Fraxinus* spp., *Gleditsia* spp., *Malus* spp., *Prunus* spp., *Pyrus* spp. and *Sorbus* spp., as the emissions are very variable in time and space and between different species, it is extremely necessary to continue research in order to catalogue existing urban vegetation in terms of VOC production.

The changes will affect the environmental services of the urban vegetation, such as maintenance of biodiversity – as there could be changes in the behavior of pollinating insects, seed disseminating animals, etc. that are very difficult to predict – as well as other services such as soil and water conservation, etc.:

10. More studies must be carried out to find out the degree to which climate change can, now and in the future, alter the functioning, composition, biodiversity and structure of the urban vegetation and how, with management, we can alleviate the effects and generate the appropriate adaptations.

The changes will also affect social services, such as recreational, educational and leisure uses, traditional cultural values, tourism, etc. as well as human health:

11. Human health will be affected with an increase in skin cancer (due above all to an increase in ultraviolet radiation); an increase in cases of cataracts in the eyes and an increase in food poisoning (due to the fact that heat promotes the activity of bacteria and therefore reduces safety in the food chain); a larger number of allergies (due to greater pollen production because of the high temperatures), etc.;
12. In addition, the presence of the Asian tiger mosquito (*Aedes albopictus*), if it comes to establish itself throughout Barcelona, could possibly lead to a reduction in visits to parks and gardens and will pose a latent threat of the expansion of infectious tropical diseases;
13. In the same way, it is also likely that tourism will fall in the hottest months and move to areas with greater thermal comfort, a trend that would be strengthened under the hypothesis that the sea level will rise and beaches disappear;
14. In this sense, it is clear that, with an increase in temperatures, all social services will be reduced in the summer as well as during the hottest times of day (as more marked temperature differences are forecast in summer than in winter). So, it would be preferable to plant shady trees that reduce the air temperature as much as possible. These trees might include: *Broussonetia papyrifera*, *Morus alba*, *Celtis australis* and *Platanus spp*.

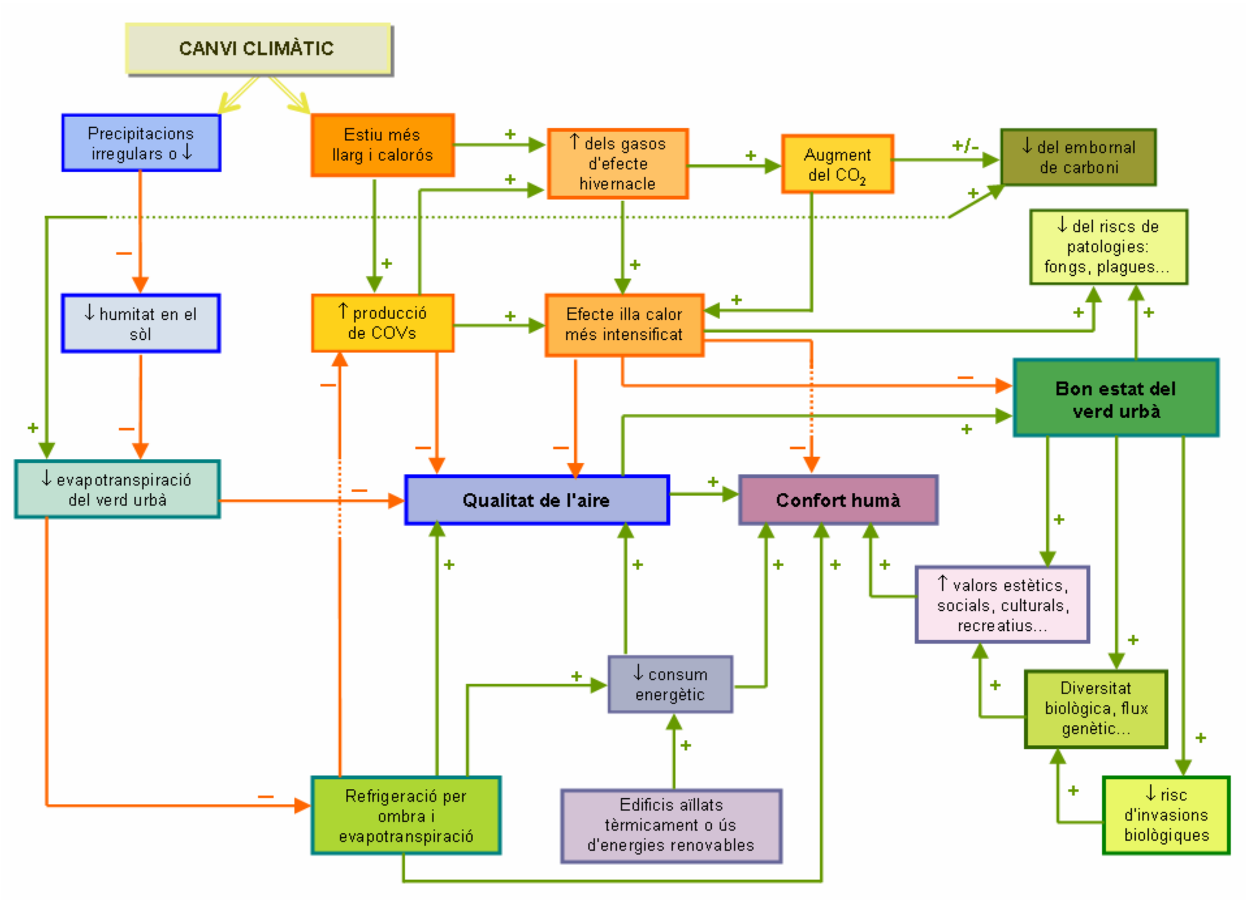
The heat island effect will be more marked because of the thermal inertia of the construction materials used and the urban structure (tall buildings contribute to forming a heat trap). In addition, energy consumption for air conditioning will be greater due to the increase in temperatures:

15. In this sense, it is clear that the establishment of green roof terraces and façades and planting deciduous trees well orientated with respect to the building can increase thermal comfort and considerably reduce electricity costs;
16. Another recommendation, when the previous one is not possible, would be to install solar panels in order to avoid carbon emissions due to increased energy consumption as far as possible. There are now solar panels compatible with green roof terraces. Technically, it is even easier to install thermo-solar capture systems for heating water;
17. The tree cover in Barcelona is 25.2% and, if we exclude the area of Collserola and Montjuïc, this cover is reduced to approximately 12.5%. It is therefore inevitable that we should recommend an increase in urban vegetation of all kinds, above all taking into account a compact model of city like ours. This increase can be achieved by planting trees on permeable surfaces and on wasteland throughout the city, creating green corridors and greenbelts connecting the city with peri-urban areas, increasing

gardens in block interiors, and establishing plant walls, dividing walls and green terraces to increase thermal insulation.

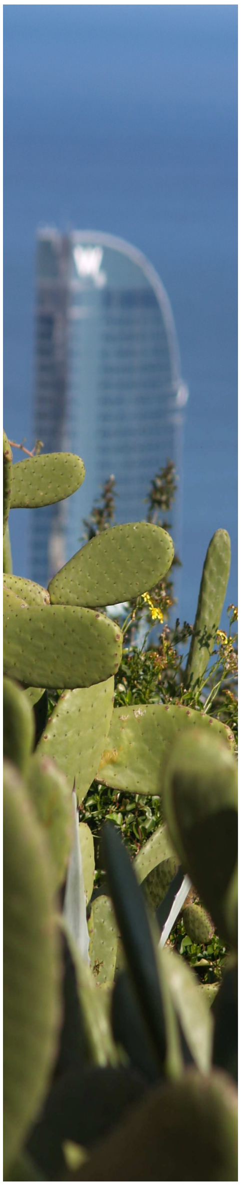
Greening strategies are not always harmless. Making the city more porous involves risks, such as facilitating the expansion of species that could invade the natural environment from the city together with the transmission of diseases from pets to wild animals. The implementation of measures such as connections between the city and the peripheral ecosystems must therefore be accompanied by rigorous measures concerning exotic species, along with regular monitoring.

Figure 19. Diagram showing the possible consequences of climate change on urban forest.



Appendix VI shows the same graph indicating the connections most susceptible to being altered by management.

CONCLUSION



The vulnerability of urban vegetation to climate change is very difficult to quantify. However, in Barcelona's parks and gardens these changes could be mitigated by appropriate management. As well as increasing the permeable surface (which, as has been seen, is only 36%) and the tree cover, the health of trees must be improved with specific watering and maintenance systems depending on the requirements of the species to promote tree growth, make them less vulnerable to drought, and improve the benefits they bring to the climate and pollution elimination. This must be accompanied by measures tending to make maintenance activities more sustainable.

This study, focusing on the environmental benefits of urban vegetation, has revealed very interesting results. However, in order to obtain other information, such as energy savings or which species best filter polluted air, it would have to be completed with eco-physiological studies, at least of the most abundant plant varieties in the city, as we already know that some species are more affected than others by warming and drought episodes. So, the choice of species through research and genetic selection could improve the state of the city's trees and ensure greater biodiversity, thereby reducing the risk from pests. Measures are also required to prevent the proliferation of invasive species in natural areas.

Due to Barcelona's great population density, the environmental services of the urban vegetation play a modest role; by contrast their social services, not included in this study, are more important, due to the need (biophilia) varying from person to person, to enjoy the presence of vegetation in streets, balconies, gardens, etc. and the improvements to the landscape this involves.

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UFORE methods 2008: Link

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Appendix I: Number of trees, carbon stored, net and gross carbon sequestered, leaf area and leaf biomass by specie.

	Number of trees	C stored (t)	Gross C sequestered (t/year)	Net C sequestered (t/year)	Leaf area (km2)	Leaf biomass (t)
Quercus ilex	313 372	21 005.5	1 472.5	1 373.2	9.983	916.14
Pinus halepensis	290 525	15 888.9	687.7	484.1	15.591	1 502.63
Platanus x acerifolia	93 212	24 453.3	1 098.5	1 008.2	20.318	887.23
Pinus pinea	69 749	4 885.2	205.8	172.6	5.757	554.90
Ailanthus altissima	37 473	940.0	75.5	66.7	1.160	86.21
Cupressus macrocarpa	32 594	826.4	55.3	52.3	0.801	187.62
Celtis australis	30 529	3 173.9	189.5	180.9	4.967	292.77
Rhamnus alaternus	30 398	406.5	54.9	53.7	0.910	40.45
Ligustrum lucidum	28 972	1 158.7	104.3	99.2	0.868	78.91
Cupressus sempervirens	28 601	3 550.2	95.9	-42.1	2.154	504.84
Robinia pseudoacacia	25 694	2 656.8	179.6	171.4	2.297	123.66
Arbutus unedo	24 172	518.9	55.7	53.9	0.550	40.85
Erica arborea	21 244	266.6	35.8	35.1	0.201	14.89
Tipuana tipu	20 518	2 656.1	161.9	152.4	2.221	165.01
Laurus nobilis	20 408	722.5	54.2	46.9	0.669	49.68
Olea europaea	16 614	1 529.4	83.8	79.6	0.687	51.00
Phoenix canariensis	15 716	274.2	3.7	3.0	1.446	242.47
Quercus cerrioides	14 438	2 514.6	121.6	112.7	1.058	97.13
Melia azedarach	13 583	1 528.9	100.2	95.2	1.115	82.86
Ulmus pumila	11 132	1 081.4	63.8	60.4	0.798	54.38
Quercus pubescens	10 826	1 142.1	63.3	56.9	0.549	36.58
Populus alba	10 217	2 071.1	66.6	61.8	0.784	68.21
Brachychiton populneum	8 544	616.7	50.9	49.2	0.277	24.28
Magnolia grandiflora	9 098	524.7	50.5	49.2	0.380	51.28
Acer negundo	8 031	672.9	47.5	41.6	0.634	58.03
Pittosporum tobira	7 869	163.9	24.4	23.7	0.201	14.95
Ceratonia siliqua	6 820	1 790.5	70.6	63.9	0.599	44.52
Elaeagnus angustifolia	7 451	85.9	13.0	12.6	0.176	13.06
Ulmus minor	6 045	581.5	37.8	34.6	0.957	65.17
Firmiana simplex	6 384	495.0	30.0	22.8	0.424	31.47
Prunus dulcis	5 687	88.4	13.7	13.3	0.797	80.67
Ulmus glabra	5 190	76.1	10.1	9.9	0.181	12.36
Rhamnus sp.	5 636	42.3	7.5	7.4	0.080	3.58
Juniperus oxycedrus	6 200	40.4	4.0	3.7	0.096	26.74
Washingtonia robusta	5 509	73.6	1.6	1.3	0.170	26.19
Chamaerops humilis	5 463	25.8	0.6	0.5	0.135	22.59
Yucca aloifolia	5 450	28.7	0.6	0.5	0.140	23.47
Aloe arborescens	4 924	1 232.1	67.8	63.1	0.018	1.33
Gleditsia triacanthos	4 266	728.1	39.7	36.9	0.314	32.93
Sophora japonica	4 182	306.9	25.0	23.6	0.328	37.25
Schinus molle	4 229	158.7	22.0	21.1	0.283	21.02
Cedrus atlantica	4 543	647.7	23.5	21.5	0.696	163.15
Pinus pinaster	4 425	1 096.6	27.1	20.4	0.731	70.48

Continued

	Number of trees	C stored (t)	Gross C sequestered (t/year)	Net C sequestered (t/year)	Leaf area (km2)	Leaf biomass (t)
Cercis siliquastrum	4 652	215.1	18.0	16.1	0.236	15.11
Abies alba	4 323	282.2	13.2	10.7	0.163	23.02
Quercus coccifera	4 335	65.6	8.4	8.1	0.089	8.21
Casuarina cunninghamiana	2 332	523.6	28.3	25.8	0.255	18.98
Tilia europaea	2 734	626.9	22.4	21.0	0.730	33.94
Jacaranda mimosifolia	2 712	287.7	19.9	18.7	0.242	18.01
Tamarix gallica	2 588	141.6	16.5	15.9	0.091	6.76
Fraxinus excelsior	3 124	193.3	19.6	18.8	0.384	40.86
Prunus cerasifera	2 820	227.0	17.1	16.4	0.117	7.11
Populus simonii	2 528	131.4	15.0	14.1	0.194	13.98
Casuarina equisetifolia	2 259	504.7	15.3	12.5	0.425	46.94
Parkinsonia aculeata	3 265	77.7	13.0	13.0	0.294	21.83
Citrus aurantium	2 712	106.8	11.3	10.6	0.048	6.50
Ficus elastica	2 540	42.8	8.3	7.7	0.061	4.57
Nerium oleander	3 235	83.3	9.9	9.6	0.067	9.95
Mespilus germanica	2 153	35.8	6.3	6.2	0.095	7.04
Ficus carica	3 456	127.3	9.6	9.3	0.136	10.11
Pistacia lentiscus	2 577	64.2	6.9	6.7	0.063	6.49
Quercus suber	3 256	62.1	7.2	7.0	0.040	7.12
Tilia euchlora	3 460	342.9	17.8	7.4	0.697	32.44
Phillyrea latifolia	3 468	49.9	6.3	6.2	0.095	4.23
Prunus avium	3 219	33.2	5.2	5.1	0.091	7.06
Albizia julibrissin	3 430	10.7	3.1	3.0	0.077	3.33
Juniperus communis	3 468	31.2	2.9	1.9	0.067	18.49
Butia capitata	2 441	1.8	0.1	0.1	0.019	3.23
Populus nigra	2 525	181.1	10.9	-5.3	0.093	6.71
Eucalyptus camaldulensis	1 172	1 193.4	22.2	19.5	0.374	51.70
Phoenix dactylifera	1 642	908.9	27.4	25.8	0.044	3.27
Cocculus laurifolius	1 172	454.2	16.4	15.4	0.242	17.99
Phytolacca dioica	1 636	797.4	23.3	20.6	0.247	18.38
Broussonetia papyrifera	781	239.2	9.4	8.9	0.118	6.77
Salix alba	1 215	269.0	13.2	12.1	0.160	9.88
Populus x canadensis	781	222.4	8.5	7.7	0.118	10.90
Morus alba	843	131.2	8.7	8.1	0.163	11.92
Tilia platyphyllos	781	219.0	7.4	6.9	0.091	5.36
Acacia saligna	855	126.5	7.5	7.0	0.108	26.12
Celtis occidentalis	843	35.3	5.1	5.1	0.109	5.65
Coriaria myrtifolia	1 172	85.9	6.1	5.9	0.028	2.09
Fraxinus ornus	812	31.4	4.0	3.9	0.051	4.11
Cedrus deodara	812	100.3	4.0	3.7	0.341	79.93
Eriobotrya japonica	920	28.1	4.3	4.2	0.017	1.23
Yucca guatemalensis	2 076	161.2	9.4	9.0	0.011	0.85
Catalpa bignonioides	1 264	25.6	5.5	5.4	0.036	1.94
Acacia retinodes	1 258	65.9	5.5	5.3	0.045	10.90
Calocedrus decurrens	781	104.9	3.6	3.3	0.109	25.54
Euonymus japonica	1 624	82.6	6.6	6.3	0.074	5.52
Fraxinus angustifolia	1 598	27.1	5.6	5.6	0.063	5.06
Wisteria sinensis	781	24.4	2.5	2.5	0.029	2.14
Punica granatum	781	16.6	2.0	2.0	0.023	1.67

Continued

	Number of trees	C stored (t)	Gross C sequestered (t/year)	Net C sequestered (t/year)	Leaf area (km2)	Leaf biomass (t)
Koelreuteria paniculata	1 732	15.1	3.7	3.6	0.035	2.81
Citrus limon	843	4.6	1.5	1.5	0.003	0.45
Pyrus communis	781	6.3	1.2	1.1	0.005	0.38
Ficus benjamina	1 264	5.4	1.8	1.8	0.004	0.27
Buxus sempervirens	1 202	5.2	1.7	1.6	0.010	0.72
Pinus radiata	1 301	17.4	1.5	1.4	0.023	2.26
Prunus americana	932	6.6	1.0	0.9	0.020	1.51
Spartium junceum	1 734	10.8	1.7	1.7	0.018	5.23
Viburnum tinus	1 734	6.8	1.6	1.6	0.030	2.19
Bougainvillea glabra	1 172	3.4	1.0	1.0	0.004	0.31
Cordyline sp.	1 342	0.4	0.0	0.0	0.006	0.47
Tilia tomentosa	334	105.9	3.4	3.2	0.052	2.44
Acer platanoides	391	79.1	3.6	3.4	0.006	0.33
Casuarina sp.	685	146.9	6.8	5.4	0.046	3.39
Populus alba var. nivea	421	35.4	3.3	3.3	0.016	1.40
Sambucus nigra	421	24.5	2.9	2.8	0.025	1.85
Acer pseudoplatanus	421	20.4	2.5	2.4	0.005	0.38
Corynocarpus laevigatus	391	34.7	2.3	2.2	0.036	2.70
Erythrina crista-galli	421	14.3	2.4	2.4	0.009	0.68
Bauhinia forficata	391	31.0	2.2	2.1	0.010	0.78
Eucalyptus globulus	434	219.4	5.4	2.2	0.052	6.71
Prunus cerasifera var. nigra	421	6.3	1.7	1.6	0.009	0.66
Maclura pomifera	421	6.8	1.6	1.6	0.006	0.63
Acacia dealbata	421	7.8	1.5	1.4	0.022	5.32
Brugmansia Spp.	421	5.7	1.4	1.4	0.005	0.34
Ligustrum vulgare	391	12.2	1.2	1.2	0.017	1.51
Pyracantha angustifolia	421	3.8	1.2	1.1	0.004	0.33
Ginkgo biloba	391	8.1	1.0	1.0	0.005	0.20
Alnus glutinosa	391	2.9	1.0	1.0	0.005	0.37
Prunus domestica	334	5.0	0.8	0.8	0.025	1.94
Cistus albidus	391	6.8	0.9	0.9	0.011	0.80
Thuja occidentalis	421	10.8	0.9	0.8	0.038	7.32
Crataegus laevigata	421	1.9	0.7	0.6	0.006	0.43
Ligustrum ovalifolium	391	3.0	0.6	0.6	0.002	0.22
Rosmarinus officinalis	434	2.7	0.5	0.5	0.004	1.00
Ligustrum japonicum	391	2.1	0.3	0.3	0.024	2.18
Juniperus phoenica	434	5.4	0.4	0.4	0.002	0.53
Schinus polygamus	434	1.2	0.4	0.4	0.001	0.05
Juglans nigra	421	1.2	0.3	0.3	0.003	0.23
Taxus baccata	499	1.3	0.3	0.3	0.009	1.03
Crataegus monogyna	434	1.3	0.3	0.3	0.000	0.05
Magnolia macrophylla	421	0.2	0.2	0.2	0.015	1.03
Bupleurum fruticosum	434	0.3	0.2	0.2	0.001	0.23
Washingtonia filifera	391	11.8	0.1	0.1	0.049	7.56
Phoenix reclinata	391	6.9	0.1	0.1	0.041	6.82
Musa x paradisiaca	421	0.1	0.0	0.0	0.001	0.09

Appendix II: Average carbon stored, net and gross carbon sequestered, leaf area and leaf biomass by individual and by specie.

**Sorted by descending order of net C sequestered per individual.*

	C stored Kg/individual		Gross C sequestered Kg/individual		Net C sequestered Kg/individual		Leaf area (m2)/individual		Leaf biomass (Kg)/individual	
	N	%	N	%	N	%	N	%	N	%
Eucalyptus camaldulensis	1 018.28	8.72%	18.94	3.04%	16.66	2.96%	319.11	3.73%	44.11	4.94%
Phoenix dactylifera	553.55	4.74%	16.69	2.68%	15.72	2.80%	26.8	0.31%	1.99	0.22%
Cocculus laurifolius	387.51	3.32%	13.99	2.24%	13.11	2.33%	206.48	2.41%	15.35	1.72%
Aloe arborescens	250.23	2.14%	13.76	2.21%	12.81	2.28%	3.66	0.04%	0.27	0.03%
Phytolacca dioica	487.4	4.18%	14.24	2.28%	12.59	2.24%	150.98	1.76%	11.23	1.26%
Broussonetia papyrifera	306.3	2.62%	12.09	1.94%	11.38	2.03%	151.09	1.76%	8.67	0.97%
Casuarina cunninghamiana	224.55	1.92%	12.15	1.95%	11.07	1.97%	109.35	1.28%	8.14	0.91%
Platanus x acerifolia	262.34	2.25%	11.79	1.89%	10.82	1.93%	217.98	2.55%	9.52	1.07%
Salix alba	221.38	1.90%	10.88	1.74%	9.93	1.77%	131.69	1.54%	8.13	0.91%
Populus x canadensis	284.74	2.44%	10.85	1.74%	9.9	1.76%	151.09	1.76%	13.96	1.56%
Morus alba	155.62	1.33%	10.27	1.65%	9.64	1.72%	193.36	2.26%	14.14	1.58%
Tilia tomentosa	317.01	2.72%	10.21	1.64%	9.49	1.69%	155.69	1.82%	7.31	0.82%
Ceratonia siliqua	262.54	2.25%	10.35	1.66%	9.37	1.67%	87.83	1.03%	6.53	0.73%
Tilia platyphyllos	280.4	2.40%	9.49	1.52%	8.85	1.57%	116.52	1.36%	6.86	0.77%
Acer platanoides	202.2	1.73%	9.18	1.47%	8.72	1.55%	15.35	0.18%	0.84	0.09%
Gleditsia triacanthos	170.68	1.46%	9.3	1.49%	8.65	1.54%	73.61	0.86%	7.72	0.86%
Acacia saligna	147.92	1.27%	8.81	1.41%	8.23	1.47%	126.32	1.48%	30.55	3.42%
Casuarina sp.	214.48	1.84%	9.97	1.60%	7.93	1.41%	67.15	0.78%	4.95	0.55%
Populus alba var. nivea	84.09	0.72%	7.91	1.27%	7.86	1.40%	38	0.44%	3.33	0.37%
Quercus cerrioides	174.17	1.49%	8.42	1.35%	7.81	1.39%	73.28	0.86%	6.73	0.75%
Tilia europaea	229.31	1.96%	8.19	1.31%	7.67	1.36%	267.01	3.12%	12.41	1.39%
Tipuana tipu	129.45	1.11%	7.89	1.27%	7.43	1.32%	108.25	1.26%	8.04	0.90%
Melia azedarach	112.56	0.96%	7.37	1.18%	7.01	1.25%	82.09	0.96%	6.1	0.68%
Jacaranda mimosifolia	106.07	0.91%	7.32	1.17%	6.9	1.23%	89.23	1.04%	6.64	0.74%
Robinia pseudoacacia	103.4	0.89%	6.99	1.12%	6.67	1.19%	89.4	1.04%	4.81	0.54%
Sambucus nigra	58.24	0.50%	6.86	1.10%	6.6	1.18%	59.38	0.69%	4.39	0.49%
Tamarix gallica	54.71	0.47%	6.36	1.02%	6.14	1.09%	35.16	0.41%	2.61	0.29%
Populus alba	202.72	1.74%	6.52	1.04%	6.05	1.08%	76.73	0.90%	6.68	0.75%
Fraxinus excelsior	61.88	0.53%	6.27	1.01%	6.01	1.07%	122.92	1.44%	13.08	1.46%
Celtis occidentalis	41.86	0.36%	6.03	0.97%	5.99	1.07%	129.3	1.51%	6.7	0.75%
Celtis australis	103.96	0.89%	6.21	1.00%	5.92	1.05%	162.7	1.90%	9.59	1.07%
Prunus cerasifera	80.5	0.69%	6.06	0.97%	5.8	1.03%	41.49	0.48%	2.52	0.28%
Brachychiton populneum	72.18	0.62%	5.95	0.95%	5.76	1.02%	32.42	0.38%	2.84	0.32%
Acer pseudoplatanus	48.48	0.42%	5.94	0.95%	5.75	1.02%	11.88	0.14%	0.9	0.10%
Corynocarpus laevigatus	88.64	0.76%	5.93	0.95%	5.73	1.02%	92.07	1.08%	6.91	0.77%
Ulmus minor	96.19	0.82%	6.25	1.00%	5.72	1.02%	158.31	1.85%	10.78	1.21%
Sophora japonica	73.4	0.63%	5.98	0.96%	5.65	1.01%	78.43	0.92%	8.91	1.00%
Erythrina crista-galli	33.85	0.29%	5.77	0.93%	5.61	1.00%	21.38	0.25%	1.62	0.18%
Populus simonii	51.96	0.45%	5.95	0.95%	5.59	1.00%	76.74	0.90%	5.53	0.62%
Casuarina equisetifolia	223.4	1.91%	6.76	1.08%	5.55	0.99%	188.14	2.20%	20.78	2.33%
Ulmus pumila	97.15	0.83%	5.73	0.92%	5.42	0.97%	71.69	0.84%	4.89	0.55%
Magnolia grandiflora	57.67	0.49%	5.56	0.89%	5.41	0.96%	41.77	0.49%	5.64	0.63%
Bauhinia forficata	79.34	0.68%	5.55	0.89%	5.37	0.96%	25.58	0.30%	1.99	0.22%

Continued

	C stored Kg/individual		Gross C sequestered Kg/individual		Net C sequestered Kg/individual		Leaf area (m2)/individual		Leaf biomass (Kg)/individual	
	N	%	N	%	N	%	N	%	N	%
Quercus pubescens	105.5	0.90%	5.85	0.94%	5.25	0.94%	50.71	0.59%	3.38	0.38%
Acer negundo	83.79	0.72%	5.92	0.95%	5.18	0.92%	78.94	0.92%	7.23	0.81%
Coriaria myrtifolia	73.3	0.63%	5.2	0.83%	5.02	0.89%	23.89	0.28%	1.78	0.20%
Eucalyptus globulus	505.62	4.33%	12.47	2.00%	5	0.89%	119.82	1.40%	15.46	1.73%
Schinus molle	37.52	0.32%	5.2	0.83%	4.98	0.89%	66.92	0.78%	4.97	0.56%
Olea europaea	92.06	0.79%	5.04	0.81%	4.79	0.85%	41.35	0.48%	3.07	0.34%
Fraxinus ornus	38.66	0.33%	4.94	0.79%	4.77	0.85%	62.81	0.73%	5.06	0.57%
Cedrus atlantica	142.57	1.22%	5.17	0.83%	4.72	0.84%	153.2	1.79%	35.91	4.02%
Pinus pinaster	247.81	2.12%	6.13	0.98%	4.61	0.82%	165.2	1.93%	15.93	1.78%
Cedrus deodara	123.46	1.06%	4.95	0.79%	4.58	0.82%	419.95	4.90%	98.44	11.03%
Eriobotrya japonica	30.54	0.26%	4.71	0.75%	4.58	0.81%	18.48	0.22%	1.34	0.15%
Quercus ilex	67.03	0.57%	4.7	0.75%	4.38	0.78%	31.86	0.37%	2.92	0.33%
Yucca guatemalensis	77.63	0.67%	4.53	0.73%	4.35	0.77%	5.3	0.06%	0.41	0.05%
Catalpa bignonioides	20.28	0.17%	4.32	0.69%	4.23	0.75%	28.48	0.33%	1.53	0.17%
Acacia retinodes	52.35	0.45%	4.33	0.69%	4.21	0.75%	35.77	0.42%	8.66	0.97%
Calocedrus decurrens	134.25	1.15%	4.57	0.73%	4.2	0.75%	139.56	1.63%	32.7	3.66%
Parkinsonia aculeata	23.8	0.20%	3.99	0.64%	3.97	0.71%	90.05	1.05%	6.69	0.75%
Euonymus japonica	50.83	0.44%	4.08	0.65%	3.9	0.69%	45.57	0.53%	3.4	0.38%
Citrus aurantium	39.38	0.34%	4.16	0.67%	3.9	0.69%	17.7	0.21%	2.4	0.27%
Prunus cerasifera var. nigra	14.85	0.13%	3.94	0.63%	3.87	0.69%	21.38	0.25%	1.57	0.18%
Maclura pomifera	16.08	0.14%	3.78	0.61%	3.71	0.66%	14.25	0.17%	1.5	0.17%
Firmiana simplex	77.54	0.66%	4.7	0.75%	3.57	0.63%	66.42	0.78%	4.93	0.55%
Fraxinus angustifolia	16.96	0.15%	3.52	0.56%	3.5	0.62%	39.42	0.46%	3.17	0.35%
Cercis siliquastrum	46.24	0.40%	3.87	0.62%	3.46	0.62%	50.73	0.59%	3.25	0.36%
Ligustrum lucidum	39.99	0.34%	3.6	0.58%	3.42	0.61%	29.96	0.35%	2.72	0.31%
Acacia dealbata	18.53	0.16%	3.44	0.55%	3.42	0.61%	52.26	0.61%	12.64	1.42%
Brugmansia Spp.	13.59	0.12%	3.42	0.55%	3.35	0.60%	11.88	0.14%	0.81	0.09%
Wisteria sinensis	31.27	0.27%	3.25	0.52%	3.18	0.57%	37.13	0.43%	2.74	0.31%
Ligustrum vulgare	31.3	0.27%	3.15	0.50%	3.07	0.55%	43.48	0.51%	3.86	0.43%
Ficus elastica	16.83	0.14%	3.28	0.53%	3.04	0.54%	24.02	0.28%	1.8	0.20%
Pittosporum tobira	20.83	0.18%	3.1	0.50%	3.01	0.54%	25.54	0.30%	1.9	0.21%
Nerium oleander	25.76	0.22%	3.07	0.49%	2.98	0.53%	20.71	0.24%	3.08	0.34%
Mespilus germanica	16.63	0.14%	2.92	0.47%	2.86	0.51%	44.12	0.52%	3.27	0.37%
Pyracantha angustifolia	9.1	0.08%	2.76	0.44%	2.71	0.48%	9.5	0.11%	0.78	0.09%
Ficus carica	36.84	0.32%	2.78	0.45%	2.69	0.48%	39.35	0.46%	2.93	0.33%
Pistacia lentiscus	24.92	0.21%	2.68	0.43%	2.61	0.46%	24.45	0.29%	2.52	0.28%
Punica granatum	21.22	0.18%	2.57	0.41%	2.52	0.45%	29.45	0.34%	2.14	0.24%
Ginkgo biloba	20.69	0.18%	2.56	0.41%	2.51	0.45%	12.79	0.15%	0.51	0.06%
Abies alba	65.27	0.56%	3.05	0.49%	2.48	0.44%	37.71	0.44%	5.33	0.60%
Pinus pinea	70.04	0.60%	2.95	0.47%	2.47	0.44%	82.54	0.96%	7.96	0.89%
Alnus glutinosa	7.52	0.06%	2.48	0.40%	2.43	0.43%	12.79	0.15%	0.95	0.11%
Prunus dulcis	15.54	0.13%	2.41	0.39%	2.34	0.42%	140.14	1.64%	14.18	1.59%
Laurus nobilis	35.4	0.30%	2.66	0.43%	2.3	0.41%	32.78	0.38%	2.43	0.27%
Prunus domestica	14.82	0.13%	2.31	0.37%	2.25	0.40%	74.85	0.87%	5.81	0.65%
Arbutus unedo	21.47	0.18%	2.3	0.37%	2.23	0.40%	22.75	0.27%	1.69	0.19%
Cistus albidus	17.37	0.15%	2.23	0.36%	2.2	0.39%	28.13	0.33%	2.05	0.23%
Quercus suber	19.07	0.16%	2.21	0.35%	2.15	0.38%	12.29	0.14%	2.19	0.24%

Continued

	C stored Kg/individual		Gross C sequestered Kg/individual		Net C sequestered Kg/individual		Leaf area (m2)/individual		Leaf biomass (Kg)/individual	
	N	%	N	%	N	%	N	%	N	%
Tilia euchlora	99.1	0.85%	5.15	0.83%	2.15	0.38%	201.45	2.35%	9.38	1.05%
Koelreuteria paniculata	8.72	0.07%	2.12	0.34%	2.07	0.37%	20.21	0.24%	1.62	0.18%
Thuja occidentalis	25.65	0.22%	2.07	0.33%	1.97	0.35%	90.26	1.05%	17.39	1.95%
Ulmus glabra	14.66	0.13%	1.94	0.31%	1.9	0.34%	34.87	0.41%	2.38	0.27%
Quercus coccifera	15.14	0.13%	1.94	0.31%	1.87	0.33%	20.53	0.24%	1.89	0.21%
Ailanthus altissima	25.08	0.21%	2.01	0.32%	1.78	0.32%	30.96	0.36%	2.3	0.26%
Phillyrea latifolia	14.39	0.12%	1.81	0.29%	1.78	0.32%	27.39	0.32%	1.22	0.14%
Rhamnus alaternus	13.37	0.11%	1.81	0.29%	1.77	0.31%	29.94	0.35%	1.33	0.15%
Citrus limon	5.43	0.05%	1.83	0.29%	1.77	0.31%	3.56	0.04%	0.53	0.06%
Elaeagnus angustifolia	11.53	0.10%	1.74	0.28%	1.69	0.30%	23.62	0.28%	1.75	0.20%
Pinus halepensis	54.69	0.47%	2.37	0.38%	1.67	0.30%	53.66	0.63%	5.17	0.58%
Erica arborea	12.55	0.11%	1.68	0.27%	1.65	0.29%	9.46	0.11%	0.7	0.08%
Cupressus macrocarpa	25.35	0.22%	1.7	0.27%	1.6	0.29%	24.58	0.29%	5.76	0.64%
Prunus avium	10.3	0.09%	1.6	0.26%	1.57	0.28%	28.27	0.33%	2.19	0.25%
Crataegus laevigata	4.61	0.04%	1.54	0.25%	1.52	0.27%	14.25	0.17%	1.02	0.11%
Pyrus communis	8.02	0.07%	1.47	0.24%	1.46	0.26%	6.4	0.07%	0.49	0.05%
Ficus benjamina	4.3	0.04%	1.46	0.23%	1.44	0.26%	3.16	0.04%	0.21	0.02%
Ligustrum ovalifolium	7.7	0.07%	1.43	0.23%	1.43	0.25%	5.12	0.06%	0.56	0.06%
Buxus sempervirens	4.33	0.04%	1.37	0.22%	1.36	0.24%	8.32	0.10%	0.6	0.07%
Rhamnus sp.	7.51	0.06%	1.34	0.21%	1.31	0.23%	14.19	0.17%	0.64	0.07%
Rosmarinus officinalis	6.24	0.05%	1.18	0.19%	1.15	0.21%	9.22	0.11%	2.3	0.26%
Pinus radiata	13.34	0.11%	1.17	0.19%	1.11	0.20%	17.68	0.21%	1.74	0.19%
Prunus americana	7.04	0.06%	1.11	0.18%	0.98	0.17%	21.46	0.25%	1.62	0.18%
Spartium junceum	6.2	0.05%	0.99	0.16%	0.97	0.17%	10.38	0.12%	3.02	0.34%
Viburnum tinus	3.94	0.03%	0.93	0.15%	0.92	0.16%	17.3	0.20%	1.26	0.14%
Albizia julibrissin	3.12	0.03%	0.89	0.14%	0.87	0.16%	22.45	0.26%	0.97	0.11%
Ligustrum japonicum	5.32	0.05%	0.87	0.14%	0.84	0.15%	61.38	0.72%	5.58	0.62%
Bougainvillea glabra	2.94	0.03%	0.82	0.13%	0.81	0.14%	3.41	0.04%	0.26	0.03%
Juniperus phoenica	12.53	0.11%	1.01	0.16%	0.81	0.14%	4.61	0.05%	1.22	0.14%
Schinus polygamus	2.83	0.02%	0.83	0.13%	0.81	0.14%	2.3	0.03%	0.12	0.01%
Juglans nigra	2.76	0.02%	0.81	0.13%	0.78	0.14%	7.13	0.08%	0.55	0.06%
Taxus baccata	2.55	0.02%	0.68	0.11%	0.66	0.12%	18.04	0.21%	2.06	0.23%
Juniperus oxycedrus	6.52	0.06%	0.64	0.10%	0.6	0.11%	15.48	0.18%	4.31	0.48%
Crataegus monogyna	2.9	0.02%	0.62	0.10%	0.58	0.10%	0	0.00%	0.12	0.01%
Juniperus communis	8.98	0.08%	0.83	0.13%	0.56	0.10%	19.32	0.23%	5.33	0.60%
Magnolia macrophylla	0.55	0.00%	0.5	0.08%	0.5	0.09%	35.63	0.42%	2.45	0.27%
Bupleurum fruticosum	0.71	0.01%	0.39	0.06%	0.39	0.07%	2.3	0.03%	0.53	0.06%
Washingtonia filifera	30.23	0.26%	0.36	0.06%	0.28	0.05%	125.32	1.46%	19.34	2.17%
Washingtonia robusta	13.37	0.11%	0.28	0.05%	0.23	0.04%	30.86	0.36%	4.75	0.53%
Phoenix canariensis	17.45	0.15%	0.24	0.04%	0.19	0.03%	92.01	1.07%	15.43	1.73%
Phoenix reclinata	17.75	0.15%	0.2	0.03%	0.18	0.03%	104.86	1.22%	17.44	1.95%
Chamaerops humilis	4.72	0.04%	0.11	0.02%	0.1	0.02%	24.71	0.29%	4.14	0.46%
Yucca aloifolia	5.27	0.05%	0.1	0.02%	0.09	0.02%	25.69	0.30%	4.31	0.48%
Butia capitata	0.75	0.01%	0.03	0.00%	0.02	0.00%	7.78	0.09%	1.32	0.15%
Musa x paradisiaca	0.21	0.00%	0.02	0.00%	0.02	0.00%	2.38	0.03%	0.21	0.02%
Cordyline sp.	0.31	0.00%	0.02	0.00%	0.02	0.00%	4.47	0.05%	0.35	0.04%
Cupressus sempervirens	124.13	1.06%	3.35	0.54%	-1.47	-0.26%	75.31	0.88%	17.65	1.98%
Populus nigra	71.71	0.61%	4.3	0.69%	-2.1	-0.37%	36.83	0.43%	2.66	0.30%

Appendix III: Leaf biomass and VOC emissions by genus.

**Sorted by descending order of VOC emission per Kg of leaf biomass.*

Genus	Leaf biomass (Kg)	Isoprene (Kg)	Monoterpene (Kg)	OVOC (Kg)	Total VOC (Kg)	VOC emission per Kg of leaf biomass*
EUCALYPTUS	58408.5	2117.7	576.6	336.2	3030.5	0.0519
CASUARINA	69314.3	2673.2	22.3	390.9	3086.4	0.0445
ROBINIA	123663.5	4621	72.4	633.1	5326.5	0.0431
POPULUS	103871	3881	30.4	531.7	4443.1	0.0428
QUERCUS	1167274.6	42703.6	679.1	5940.5	49323.2	0.0423
PLATANUS	887232.1	32729.2	258.5	4523	37510.7	0.0423
SALIX	9876.5	353.3	2.8	49.9	406	0.0411
KOELREUTERIA	2810.5	65.3	0	14.2	79.6	0.0283
PISTACIA [2]	161339.7	0	3705.4	820.6	4526	0.0281
RHAMNUS [2]	188133.2	3626.3	0	956.5	4582.8	0.0244
MYRTUS [2]	2924.4	46	0	16.9	62.9	0.0215
MAHONIA [1]	122.2	1.5	0	0.7	2.2	0.0180
FICUS	23790.1	289.2	14	122.6	425.8	0.0179
SCHINUS	21070.6	0	239.3	123.1	362.5	0.0172
ABIES	23015.8	1.3	231.2	134.8	367.2	0.0160
MAGNOLIA	52311.4	2.9	525.5	306.4	834.8	0.0160
PINUS	2297692.4	126	23062.4	13448.8	36637.2	0.0159
ACACIA	42335.3	2.3	380.7	222	605.1	0.0143
JUGLANS	227.2	0	2	1.2	3.2	0.0141
PHOENIX	252562.6	1946.4	0	1480.8	3427.1	0.0136
GINKGO	200.1	0	1.7	1	2.7	0.0135
MACLURA	625.1	4	0.4	3.2	7.6	0.0122
CITRUS	8119	0.4	43.6	47.6	91.7	0.0113
CEDRUS	243079.7	13.1	1295.2	1416.2	2724.5	0.0112
BROUSSONETIA	6768.8	37.9	3.8	33.7	75.4	0.0111
TAXUS	1033.1	0.1	5.2	6.1	11.3	0.0109
PUNICA	1672	9	0	8.3	17.3	0.0103
ACER	58748.9	3.1	272.8	298.2	574.1	0.0098
AUCUBA [1]	13701.5	0.7	63.8	69.8	134.4	0.0098
AILANTHUS	111263.7	5.7	514.5	562.6	1082.8	0.0097
CORNUS	894.6	0	4.1	4.4	8.6	0.0096
CUPRESSUS	753516	0	2045.2	4472.5	6517.6	0.0086
THUJA	28267.7	1.6	57.1	166.5	225.2	0.0080
JUNIPERUS [2]	691140.8	37.6	1384.3	4036.4	5458.4	0.0079
CALOCEDRUS	25541.6	1.3	50.3	146.7	198.3	0.0078
CORYLUS	1619.3	0.1	4.2	8.2	12.6	0.0078
ALNUS	368.8	0	0.9	1.8	2.8	0.0076
OLEA	69222.7	0	69.5	405.5	475.1	0.0069
ARBUTUS [2]	175490.2	9.6	58.8	1028	1096.4	0.0062
LAURUS	63919	3.5	21.4	374.5	399.4	0.0062
ERIOBOTRYA	1228.9	0	0	7.2	7.2	0.0059
COTONEASTER [2]	34704.7	0	0	204.6	204.6	0.0059
PITTOSPORUM [2]	246148.7	0	0	1415.9	1415.9	0.0058
GLEDITSIA	32926.5	1.8	19.3	168.6	189.6	0.0058
EUONYMUS [1]	23436	1.3	13.8	120.4	135.4	0.0058
RAPHIOLEPIS [1]	311.4	0	0	1.8	1.8	0.0058

Continued

Genus	Leaf biomass (Kg)	Isoprene (Kg)	Monoterpene (Kg)	OVOC (Kg)	Total VOC (Kg)	VOC emission per Kg of leaf biomass*
ALBIZIA	3327.4	0.2	2	17.2	19.3	0.0058
LIGUSTRUM	109199.5	0	0	636.5	636.5	0.0058
MORUS	11920.6	0.7	7.1	61.8	69.5	0.0058
BUXUS [2]	12117.1	0.6	7	61.3	68.9	0.0057
CELTIS	301196.6	15.6	174.5	1526.4	1716.5	0.0057
WISTERIA [1]	42180.3	2.2	24.6	214.8	241.6	0.0057
ELAEAGNUS	13060.1	0.6	7.4	65	73.1	0.0056
TAMARIX	6761.9	0.4	2	34.6	37	0.0055
ULMUS	132112.2	7.1	38.8	678.4	724.3	0.0055
MELIA	82856.1	4.5	24.4	426	454.8	0.0055
PRUNUS	114148.6	5.8	32.8	573.8	612.4	0.0054
FRAXINUS	50033.5	2.5	14.3	250.2	266.9	0.0053
MALUS	366.1	0	0	1.9	1.9	0.0052
CATALPA	1943.4	0	0	10.1	10.1	0.0052
VIBURNUM [1]	178348.9	0	0	905.6	905.6	0.0051
RUBUS [1]	223992.9	0	0	1139.8	1139.8	0.0051
LONICERA [1]	37005.1	0	0	188.4	188.4	0.0051
CRATAEGUS	5183.1	0	0	26.4	26.4	0.0051
JACARANDA	18013.3	0	0	92.1	92.1	0.0051
ROSA [1]	3517.8	0	0	18	18	0.0051
SAMBUCUS [2]	4090.9	0	0	21	21	0.0051
PYRUS	381.5	0	0	1.9	1.9	0.0050
FIRMIANA	31474.2	0	0	157.9	157.9	0.0050
TILIA	74180.8	0	0	374.3	374.3	0.0050
PYRACANTHA [1]	1089.4	0	0	5.5	5.5	0.0050
HIBISCUS	467.3	0	0	2.3	2.3	0.0049

1 (Shrubs): genus found only in shrub form (any woody vegetation with a DBH < 2.54 cm).

2 (Trees and shrubs): genus found in shrub form as well as in tree form (any woody vegetation with a DBH > 2.54 cm).

Appendix IV: Leaf biomass and CO emissions by genus.

***Sorted by descending order of CO formation per Kg of leaf biomass.**

Genus	Leaf biomass (Kg)	CO formed (Kg)	CO removed (Kg)	Net CO (formed-removed) Kg	Net CO per Kg of Leaf biomass*
EUCALYPTUS	58,408.5	572.7	30.8	541.9	0.0093
ROBINIA	123,663.5	1,089.0	65.2	1,023.7	0.0083
POPULUS	103,871.0	908.3	54.3	854.1	0.0082
CASUARINA	69,314.3	605.3	36.6	568.7	0.0082
PLATANUS	887,232.1	7,668.1	468.0	7,200.2	0.0081
QUERCUS	1,167,274.6	10,079.0	595.7	9,483.3	0.0081
SALIX	9,876.5	83.0	5.2	77.8	0.0079
PISTACIA	161,339.7	922.7	54.8	867.8	0.0054
KOELREUTERIA	2,810.5	16.2	1.5	14.7	0.0052
RHAMNUS	188,133.2	933.1	71.9	861.2	0.0046
MYRTUS	2,924.4	11.8	1.4	10.5	0.0036
FICUS	23,790.1	86.0	10.8	75.1	0.0032
MAHONIA	122.2	0.4	0.0	0.4	0.0031
SCHINUS	21,070.6	63.7	11.1	52.6	0.0025
JUGLANS	227.2	0.6	0.1	0.5	0.0023
ACACIA	42,335.3	120.0	22.3	97.7	0.0023
PINUS	2,297,692.4	6,431.7	1,179.2	5,252.5	0.0023
MAGNOLIA	52,311.4	147.0	27.6	119.4	0.0023
ABIES	23,015.8	64.5	12.1	52.3	0.0023
GINKGO	200.1	0.5	0.1	0.4	0.0022
PHOENIX	252,562.6	634.0	133.2	500.8	0.0020
MACLURA	625.1	1.5	0.3	1.2	0.0019
BROUSSONETIA	6,768.8	15.2	3.6	11.6	0.0017
AUCUBA	13,701.5	27.0	4.6	22.4	0.0016
CORNUS	894.6	1.7	0.3	1.4	0.0016
PUNICA	1,672.0	3.5	0.9	2.6	0.0016
AILANTHUS	111,263.7	217.3	53.8	163.5	0.0015
CITRUS	8,119.0	16.0	4.1	11.9	0.0015
ACER	58,748.9	115.2	31.0	84.2	0.0014
CEDRUS	243,079.7	474.6	128.2	346.4	0.0014
TAXUS	1,033.1	2.0	0.5	1.4	0.0014
CORYLUS	1,619.3	2.5	0.5	2.0	0.0012
JUNIPERUS	691,140.8	941.8	238.5	703.3	0.0010
CUPRESSUS	753,516.0	1,129.3	385.5	743.8	0.0010
THUJA	28,267.7	38.9	10.8	28.1	0.0010
ALNUS	368.8	0.6	0.2	0.4	0.0010
CALOCEDRUS	25,541.6	34.1	13.5	20.7	0.0008
WISTERIA	42,180.3	47.7	14.4	33.2	0.0008
BUXUS	12,117.1	13.6	4.2	9.4	0.0008
EUONYMUS	23,436.0	26.7	8.9	17.9	0.0008
OLEA	69,222.7	81.5	33.0	48.6	0.0007
ARBUTUS	175,490.2	187.5	66.3	121.3	0.0007
MALUS	366.1	0.4	0.1	0.3	0.0007
RAPHIOLEPIS	311.4	0.3	0.1	0.2	0.0007
COTONEASTER	34,704.7	34.9	11.7	23.2	0.0007
LONICERA	37,005.1	37.0	12.3	24.7	0.0007

Continued

Genus	Leaf biomass (Kg)	CO formed (Kg)	CO removed (Kg)	Net CO (formed-removed) Kg	Net CO per Kg of Leaf biomass*
ROSA	3,517.8	3.5	1.2	2.4	0.0007
RUBUS	223,992.9	223.6	74.4	149.3	0.0007
VIBURNUM	178,348.9	177.7	59.7	118.0	0.0007
CRATAEGUS	5,183.1	5.2	1.8	3.4	0.0007
PITTOSPORUM	246,148.7	245.5	84.7	160.8	0.0007
HIBISCUS	467.3	0.5	0.2	0.3	0.0006
ALBIZIA	3,327.4	3.8	1.8	2.1	0.0006
MORUS	11,920.6	13.7	6.3	7.4	0.0006
GLEDITSIA	32,926.5	37.4	17.4	20.0	0.0006
CELTIS	301,196.6	338.6	158.3	180.3	0.0006
PYRACANTHA	1,089.4	1.1	0.4	0.7	0.0006
SAMBUCUS	4,090.9	4.1	1.7	2.4	0.0006
ELAEAGNUS	13,060.1	14.4	6.9	7.5	0.0006
LAURUS	63,919.0	68.3	30.9	37.4	0.0006
MELIA	82,856.1	89.5	43.7	45.8	0.0006
PRUNUS	114,148.6	120.5	57.2	63.3	0.0006
TAMARIX	6,761.9	7.3	3.6	3.7	0.0006
ULMUS	132,112.2	142.5	69.6	72.9	0.0006
FRAXINUS	50,033.5	52.5	26.4	26.1	0.0005
LIGUSTRUM	109,199.5	108.4	52.4	56.0	0.0005
CATALPA	1,943.4	2.0	1.0	1.0	0.0005
ERIOBOTRYA	1,228.9	1.2	0.6	0.6	0.0005
JACARANDA	18,013.3	18.1	9.5	8.6	0.0005
FIRMIANA	31,474.2	31.0	16.6	14.4	0.0005
TILIA	74,180.8	73.5	39.1	34.3	0.0005
PYRUS	381.5	0.4	0.2	0.2	0.0005

Appendix V: Leaf biomass and O_3 emissions by genus.

**Sorted by descending order of O_3 formation per Kg of leaf biomass.*

Genus	Leaf biomass (Kg)	O_3 formed (Kg)	O_3 removed (Kg)	Net O_3 (formed-removed) Kg	Net O_3 per Kg of Leaf biomass*
ROBINIA	123,663.5	15,821.7	842.5	14,979.2	0.1211
POPULUS	103,871.0	13,265.5	702.3	12,563.2	0.1210
CASUARINA	69,314.3	8,838.9	472.2	8,366.7	0.1207
PLATANUS	887,232.1	111,886.9	6,044.8	105,842.2	0.1193
QUERCUS	1,167,274.6	146,206.1	7,746.5	138,459.7	0.1186
EUCALYPTUS	58,408.5	7,224.7	397.9	6,826.7	0.1169
SALIX	9,876.5	1,208.3	67.3	1,141.0	0.1155
KOELREUTERIA	2,810.5	226.1	19.1	207.0	0.0736
RHAMNUS	188,133.2	12,655.0	999.2	11,655.8	0.0620
MYRTUS	2,924.4	154.1	18.2	135.9	0.0465
MAHONIA	122.2	5.2	0.6	4.6	0.0380
FICUS	23,790.1	1,044.6	144.2	900.3	0.0378
PHOENIX	252,562.6	6,964.6	1,720.7	5,243.9	0.0208
MACLURA	625.1	15.5	4.3	11.3	0.0181
BROUSSONETIA	6,768.8	149.4	46.1	103.3	0.0153
PISTACIA	161,339.7	3,236.8	786.4	2,450.4	0.0152
PUNICA	1,672.0	34.9	11.4	23.5	0.0140
SCHINUS	21,070.6	218.6	143.6	75.1	0.0036
JUGLANS	227.2	2.3	1.5	0.7	0.0032
ACACIA	42,335.3	420.7	288.4	132.3	0.0031
PINUS	2,297,692.4	22,332.0	15,316.1	7,015.9	0.0031
MAGNOLIA	52,311.4	511.9	356.4	155.5	0.0030
ABIES	23,015.8	224.0	156.8	67.2	0.0029
GINKGO	200.1	1.8	1.4	0.5	0.0024
AUCUBA	13,701.5	92.5	65.7	26.9	0.0020
CORNUS	894.6	5.8	4.3	1.5	0.0017
CORYLUS	1,619.3	8.5	7.8	0.7	0.0004
AILANTHUS	111,263.7	741.3	707.4	33.8	0.0003
CITRUS	8,119.0	54.9	53.0	1.9	0.0002
ACER	58,748.9	394.2	400.3	-6.1	-0.0001
CEDRUS	243,079.7	1,618.7	1,656.1	-37.4	-0.0002
TAXUS	1,033.1	6.8	7.0	-0.3	-0.0003
JUNIPERUS	691,140.8	3,152.2	3,405.0	-252.8	-0.0004
THUJA	28,267.7	131.2	150.3	-19.1	-0.0007
WISTERIA	42,180.3	157.8	206.5	-48.7	-0.0012
BUXUS	12,117.1	44.8	59.5	-14.8	-0.0012
EUONYMUS	23,436.0	89.0	123.5	-34.5	-0.0015
MALUS	366.1	1.2	1.8	-0.6	-0.0016
RAPHIOLEPIS	311.4	1.0	1.5	-0.5	-0.0016
ROSA	3,517.8	11.1	16.9	-5.7	-0.0016
LONICERA	37,005.1	115.9	177.4	-61.4	-0.0017
RUBUS	223,992.9	701.2	1,073.6	-372.4	-0.0017
COTONEASTER	34,704.7	109.9	167.9	-58.0	-0.0017
CUPRESSUS	753,516.0	3,745.6	5,010.4	-1,264.8	-0.0017
VIBURNUM	178,348.9	556.3	859.2	-303.0	-0.0017
ARBUTUS	175,490.2	617.2	923.6	-306.4	-0.0018

Continued

Genus	Leaf biomass (Kg)	O_3 formed (Kg)	O_3 removed (Kg)	Net O_3 (formed-removed) Kg	Net O_3 per Kg of Leaf biomass*
ALNUS	368.8	1.9	2.5	-0.7	-0.0018
HIBISCUS	467.3	1.4	2.2	-0.8	-0.0018
PITTOSPORUM	246,148.7	768.9	1,210.0	-441.0	-0.0018
CRATAEGUS	5,183.1	16.3	25.8	-9.5	-0.0018
PYRACANTHA	1,089.4	3.3	5.9	-2.5	-0.0023
CALOCEDRUS	25,541.6	112.6	174.0	-61.5	-0.0024
OLEA	69,222.7	261.1	434.8	-173.7	-0.0025
SAMBUCUS	4,090.9	13.0	23.3	-10.3	-0.0025
LAURUS	63,919.0	224.9	406.7	-181.8	-0.0028
MORUS	11,920.6	46.0	81.2	-35.2	-0.0030
ALBIZIA	3,327.4	12.7	22.7	-10.0	-0.0030
GLEDITSIA	32,926.5	124.3	224.3	-100.0	-0.0030
CELTIS	301,196.6	1,116.5	2,046.5	-930.0	-0.0031
PRUNUS	114,148.6	393.1	747.0	-354.0	-0.0031
ELAEAGNUS	13,060.1	46.8	89.0	-42.1	-0.0032
LIGUSTRUM	109,199.5	338.5	690.7	-352.2	-0.0032
MELIA	82,856.1	297.0	564.5	-267.5	-0.0032
ULMUS	132,112.2	472.6	899.7	-427.1	-0.0032
TAMARIX	6,761.9	24.1	46.1	-22.0	-0.0033
FRAXINUS	50,033.5	170.6	340.9	-170.3	-0.0034
CATALPA	1,943.4	6.3	13.2	-7.0	-0.0036
ERIOBOTRYA	1,228.9	3.9	8.4	-4.5	-0.0037
JACARANDA	18,013.3	56.9	122.7	-65.9	-0.0037
TILIA	74,180.8	228.9	505.4	-276.5	-0.0037
FIRMIANA	31,474.2	96.1	214.4	-118.3	-0.0038
PYRUS	381.5	1.1	2.6	-1.5	-0.0038

Appendix VI: Possible consequences of climate change on urban vegetation. ⊗: Connections most susceptible to being altered by management.