Voichita Bucur

Urban Forest Acoustics

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With 109 Figures and 33 Tables

Springer

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Preface

In general, trees are viewed as admired symbolic individuals, producing recreational, spiritual and emotional rejuvenation. Their lifespan can far exceed that of humans. Planting a tree is a singular act of faith in the future, creating a legacy for the community members who will follow. The presence of trees in an urban area has been a reality for several centuries. Beautiful trees in urban plazas are synonymous with a high sense of community and civic pride. Trees significantly enhance the landscaping and appearance of the built environment.

City trees improve several architectural and engineering functions, providing a green infrastructure for communities. Trees create a friendlier environment for walking, riding bikes and working, by reducing glare and softening harsh traffic sounds and concrete views. Trees enhance the viewing in urban areas of a variety of birds and small animals, such as squirrels. They are of extreme importance to the functioning of many different ecosystems. Trees planted in the right place around buildings can improve air conditioning and heating costs by providing shade or by affecting wind speed or direction. Evergreen trees with dense, persistent needles can be used to provide a windbreak, while deciduous trees allow the sun to warm a house in winter. The more compact the branches and foliage of a group of trees, the greater their influence as a windbreak. It has been shown that trees are able to remove pollutants from the air; and they are seen as an important potential resource for removing greenhouse gasses from the atmosphere. Trees contribute to the protection of the environment and public health, providing economic and social benefits, encouraging positive social interaction.

In a modern concept, urban forest refers to all trees and vegetation in urban and suburban areas.

My motivation for writing this book comes from the frequently asked questions about urban environmental integrity, related namely to noise, climate, air and water quality.

This book is structured in nine chapters. As usual the first chapter "Introduction" relates the concept of the urban tree in contrast to the forest tree and gives a short description of the dendrological characteristics of different trees in the urban environment. The second chapter is "Noise in Forest" and refers to sound propagation in forest and the factors affecting this propagation. The equipment for in situ noise measurement is presented. The third chapter introduces acoustical sensors for the measurement of tree characteristics (diameter, height, mechanical and genetic characteristics). Chapter 4 is devoted to noise attenuation with plants, setting aside ground attenuation, scattering by trees, foliage, trunks and branches. The last section of this chapter refers to reverberation and attenuation in a forest stand. Chapter 5 depicts a very current subject, namely, protection against traffic noise from highways, railways and aircraft. Chapter 6 – noise abatement and dwellings in urban and suburban areas – underlines the necessity to take into consideration the meanings of the soundscape, which are environmental, historical or cultural. The practical application of this concept produces sound maps for urban planning. A positive impression on the urban soundscape is produced by large vegetation areas, belts of trees, public gardens and parks. Chapter 7 offers a brief discussion on the relationships between noise, animals, insects and trees and, of course, the acoustic methods for the detection of the presence of these biological agents in different stages of development. Chapter 8 – fire control with acoustical methods – briefly describes the potential of acoustics in forest fire detection and control. Finally, it seems appropriate to end this book (Chap. 9) with some considerations about economic aspects related to the value of urban trees.

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1 Introduction

Trees are an accepted presence in the urban landscape as individuals in streets, parks and gardens or as components of woodlands as "relics" surviving from forest before urbanization, or as planted and spontaneous regenerated blocks on derelict sites. These trees are labeled *urban trees* in contrast to *forest trees*. The concept of urban forestry was developed first in Canada, during the 1960s, and was defined as a practice proposing a global approach of tree management with a view to integration with urban activity and population.

In planning housing development in urban and suburban areas, a major challenge is to manage the native forest trees as well as exotic trees. Because of the urban environment, trees could decline (Fig. 1.1), changing their size and silhouette, while at the same time being (from the pathological point of view) sound trees. Good selection criteria should be used when retaining trees on a specific site, determined by urban morphology. Generally, the criteria used for the selection and planting of urban trees are: the growth requirement of each species as described by sylvicultural practice and specific features evaluated for individual trees and stands, having in mind that trees are very long-lived individuals (300, 900 or 2000 years) if air, water, minerals from the soil and sunlight are supplied. The policy of the Green Areas and Environment Departments in many cities in the world is to preserve and develop the green heritages which have an important social, aesthetic, cultural, educational or climatic role. The need to inform and instruct people about various aspects of environmental protection is generally accepted today. The management of green urban areas requires a wider political, administrative and technical approach (Council of Europe 2004). Selection of species and technological innovations (container grown techniques, automatic watering, etc.) are crucial issues in tree renewal politics.

According to the botanical system of classification, trees fall into two groups: (a) coniferous, known as evergreens, needle-leafed trees or softwoods and (b) deciduous, known as broad-leafed trees or hardwoods. Mature softwoods have a straight central trunk, with side branches which spread to form a conical or columnar crown. The form of the hardwoods has a broad rounded crown with long branches. As a guide to general appearance, tree silhouettes are given in Fig. 1.2. For tree identification, botanists use the scientific name which consists basically of two terms: the generic name (genus) and the specific

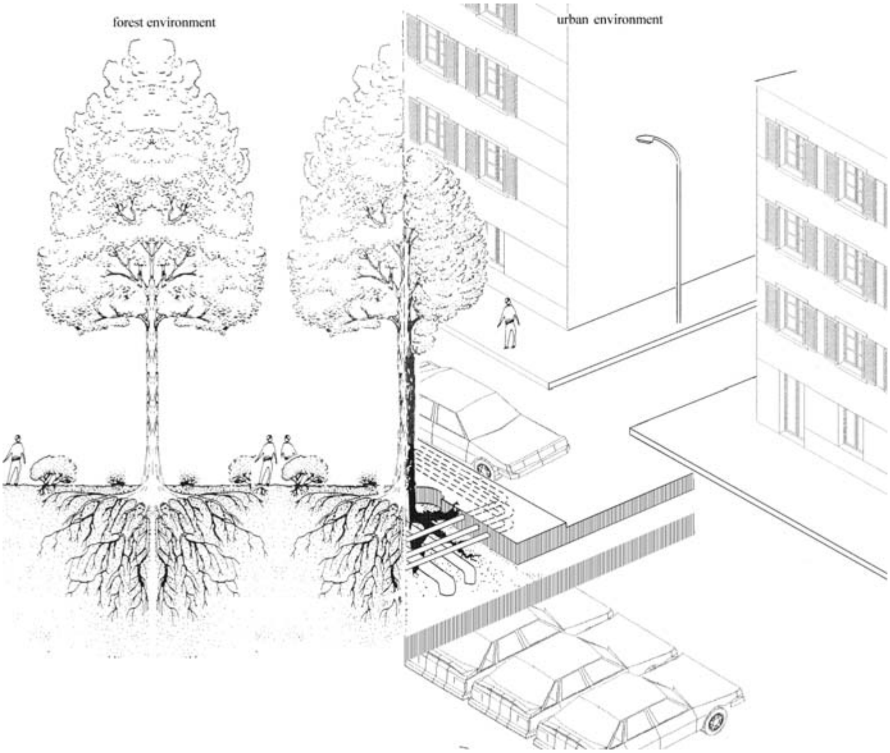

Fig. 1.1. Trees in natural and urban environments

name (species), e.g.: *Abies alba*. The specific name can be traced to several origins: Latin, Celtic, Greek, etc. (so *alba* from Latin = white; Aymonin 1986). The common name for *Abies alba* is fir, which is generally used and has been handed down from generation to generation. In this book, both scientific and common names will be used.

Considerable ecological and silvicultural information has been developed in reference books and manuals in the past century for judging how a tree or a stand should be managed. Specific features for individual trees and stands must be considered. The main criteria to select trees for urban and suburban areas are related to the growth and silvicultural requirements of each species. Following the position of a tree in a stand, trees can be classified as:

- dominant trees, with well formed crowns, receiving sunlight uniformly
- co-dominant trees, in the high canopy
- intermediate trees with crowns in the lower part of the canopy, shaded by the surroundings
- suppressed trees, with crowns below the main level of the canopy.

Fig. 1.2. Silhouettes of trees (from Hosie 1969; reproduced by permission of Natural Resources Canada, Canadian Forest Service, copyright 2005)

For each tree, the morphological and physical characteristics which must be considered are the following: height, diameter at breast height, growth ratio (radial increment rate), live crown ratio (height of crown divided by total tree height), density expressed as number of stems per hectare and general health aspect – the vigorous aspect of the tree, without insect damage or disease.

Remarkable studies by Zimmermann and Brown (1980), Wilson (1984) and Mattheck (1996, 1998) enable the reader to increase his questions and answers related to the biological and mechanical functions of trees.

Identification of native trees and plants is essential for the prediction of better growth conditions of trees in a specific site. The introduction of species like ornamental apples and cherries is used to develop the existing vegetation quickly and to satisfy the socio-economic requirements of the residents.

The street tree population is very variable and is composed of hardwoods and mixed softwoods/hardwoods, having a density of 100 trees/km of street and a diameter ranging from 10 cm to 60 cm. Deciduous trees ensure greater water evaporation and consequent cooling of the street, while mixed trees ensure a higher noise attenuation efficiency because of the evergreen species used. The diversity of urban morphology determines the structure of street tree patterns, related to the natural environment and the management policies of cities and adjacent residential or suburban zones. Table 1.1 gives some dendrometric characteristics of different species from the temperate zone.

Rapid urbanization after the First and Second World Wars altered the microclimate in urban areas, through a gradual replacement of original forest by man-made buildings and structures which increased the heat-storage capacity of cities. Street trees, as well as parks, gardens and green spaces, are natural air

Table 1.1. Some dendrological characteristics of several species growing in a forest environment (data from Hora 1981; Aymonin 1986)

Species		Height	Age (years)	
Scientific name	Common name	(m)	Maturity	Longevity
	Deciduous species			
Acer pseudoplatanus	Sycamore	30	25	200–500
Aesculus hypocastanum	Horse chestnut	25	24	200
Fagus silvatica	Common beech	45	30	300
Liriodendron tulipifera	Tulip tree	60	30	500
Quercus robur	Oak	25	45	2,000
Betula pendula	Birch	15	10	100
Populus alba	White poplar	10	5	50
Tillia cordata	Lime	35	20	500
	Coniferous species			
Picea abies	Spruce	50	50	400
Abies alba	Fir	50	15	200
Pinus strobus	Eastern white pine	80	50	200
Pinus contorta	Lodgepole pine	33	Unknown	150
Thuja plicata	Arbor vitae	60	Unknown	400
Larix decidua	Larch	35	Unknown	600
Chamaecyparis lawsoniana	False cypress	50	Unknown	400
Sequoia sempervirens	Redwood	120	Unknown	2,000

Table 1.2. Noise reduction with different patterns of street trees in Nanjing, China (data from Mao et al. 1993). The tree species are: *P.a.* = *Platanus acerifolia*; *M.g.* = *Metasequoia glyptostroboides*; *S.c.* = *Sabina chinesis; P.t.* = *Pittosporum tobira*; *C.i.* = *Carya illinoensis*; *C.d.* = *Cedrus deodara*; *E.j.* = *Euonymus japonica*

Parameters	Streets			
	No 1	No 2	No 3	No 4
Street width (m)	40	42	28	30
Tree pattern	Deciduous	Mixed	Deciduous	Mixed
Number of tree rows	6	4	2	4
Width of green belt (m)	35	35	2	4
Canopy height (m)	4–25	4–22	4–25	4–20
Crown projection (%)	80–85	80–85	85–90	80–85
Tree species	*P.a*	*M.g.*; *S.c.*; *P.t.*; *C.i.*; *E.j.*	*P.a.*	*M.g.*; *C.d.*; *C.i*
Noise attenuation (dB)	6	4	1	8
Efficiency (dB/m)	0.24	0.31	0.10	0.36

conditioners and, within a limited range, noise attenuators. Mecklenberk et al. (1972) noted that the noise attenuation capacity of trees is directly related to the density and width of planting zones. The efficiency of noise attenuation, as expressed in Table 1.2, is 0.36 dB/m for mixed zones and only 0.17 dB/m for zones planted with only one species.

The existing information in the literature on noise reduction in urban environment is quite abundantly disseminated in publications related to forest and agricultural studies during the period 1970–1990 and is very scarce later; and, in contrast, publications related to acoustic studies during the past 20 years stress the development of modeling techniques. The aim of this book is to show the necessity of understanding both aspects.

2 Noise in Urban Forest

Noise in urban forest is produced by the sound field of different sources which can be detected in the surroundings. The acoustic intensity of this field is characterized by the following parameters: the amplitude of the disturbance, the excess pressure, the particle velocity, the density change or corresponding change in refractive index, the steady pressure on a surface due to the impact of sound waves, the thermal changes produced by alternating compression and rarefaction and the power which may be absorbed from the sound waves. From a theoretical point of view, three fundamental types of sources are recognized: the simple point source, the doublet (or dipole, equivalent to two simple and equal sound sources), and the quadrupole (the combination of two doublet sources, termed longitudinal and lateral quadrupole). A simple point sound source can be produced by a single-shot propane gun source.

To study impulse source scattering in forest, Rogers et al. (1992) used a propane gun, which contains a significant amount of low-frequency acoustic energy, and a microphone located in a stand, at 10 m from the source. It was observed that the received signal is composed of two main components: (a) a direct zone produced by sound wave direct propagation from the source to the microphone and (b) a scattered zone induced by the presence of woods. Scattering phenomena in a stand are very complex and rather difficult to estimate accurately. In order to make a detailed assessment of the influences of all factors producing scattering in a forest stand (biomass, density of trees/ha, tree height, tree diameter, crown shape and size, size and shape of leaves and needles, etc.), it has been accepted to study a global parameter expressed by the excess attenuation, which includes the absorption, dispersion, reflection and refraction of sound.

The specification of noise in physical terms depends upon its nature. One of the best representations is given by its spectrum. For noise measurement, three techniques are used: recording the wave-form to identify the disturbing frequency components, narrowband analysis and broadband analysis when determining the requirements for noise control. For most purposes, it is sufficiently accurate to use octave band analysis.

In the first part of this chapter, several acoustical notions necessary for the understanding of the theoretical and practical approaches are proposed. Factors affecting sound propagation and scattering phenomena are discussed.

The second part of this section is devoted to a presentation of the equipment for noise measurements.

2.1 Sound Propagation

2.1.1 Definitions and Theoretical Considerations

The sound is produced by a disturbance induced in air, causing alternative pressure and displacement of the air molecules. The dictionary of acoustics (Morfey 2001) and basic reference books (Stephens and Bate 1966; Beranek and Vèr 1992; Fahy and Walker 1998; Harris 1998; see also sources for noise level data in journals such as: Acta Acustica, J Acoust Soc Am, J Sound Vibr, Noise Control Eng J; and the US National Bureau of Standards and the ISO standards noted in Annex 4), in an acoustical context, define noise as an undesired and extraneous sound. A sound wave can be composed of a single frequency (pure tone), or a combination of this frequency harmonically related or not.

The measurable aspects of sound propagation in air can be described by many parameters. In this book, I selected only 12 parameters, as follows:

1. *Sound pressure* is the variation in pressure above and below atmospheric pressure and is expressed in Pascals (Pa). The normal audible frequency range is roughly between 15 Hz and 16 kHz. Frequencies between 3 kHz and 6 kHz are the most sensitive. A young person can detect pressure as low as 20 µPa, compared to normal atmospheric pressure, which is 101.3×10^3 Pa.
2. *Speed of sound* in air (noted c in m/s) is calculated as:

$$c = \sqrt{\frac{1.4 P_s}{\varrho}} \tag{2.1}$$

where P_s is the ambient pressure (Pa) and ϱ is the air density (kg/m^3). The speed of sound in air is dependent on temperature. Some theoretical aspects related to this interaction are presented in Annex 3.

For practical purposes, the speed of sound is determined with the following approximate formula:

$$c = 331.4 + 0.607\theta \tag{2.2}$$

where θ is the ambient temperature in °C, or with the exact formula:

$$c = 331.4\sqrt{\frac{T}{273}} = 331.4 + \sqrt{1 + \frac{\theta}{273}} \tag{2.3}$$

where T is the absolute temperature (K). At the normal temperature of 20 °C, the speed of sound is 344.8 m/s.

3. *Sound intensity* (W/m^2) is the sound energy transmitted through a specific area and measured in a specific direction. In free space, the sound intensity is related to the total power radiated into the air by a sound source and to the sound pressure. Sound intensity at a point is a vector, having a minimum and a maximum. The maximum is obtained when its plane is perpendicular to the direction of travel; when parallel, the sound intensity is zero. The sound intensity is related to the sound pressure. In an environment without reflecting surfaces, at any point, the sound pressure of freely traveling waves (plane, cylindrical, spherical) is related to the maximum intensity $I_{\max}$, through the equation:

$$I_{\max} = \frac{p_{\text{rms}}^2}{\varrho \cdot c} \tag{2.4}$$

   where p_{rms} is the root-mean-square (rms) sound pressure (expressed in Pa or N/m^2), ϱ is the density of the air (kg/m^3), c is the speed of sound in air (m/s), $c\varrho$ is the characteristic impedance of the air $\left(\frac{\text{m}}{\text{s}} \cdot \frac{\text{kg}}{\text{m}^3}\right)$.

4. *Sound power level* is the measure of the total acoustic power radiated by a source and is expressed in dB *re* W_0, which is the reference sound power, standardized at 10^{-12} W, and is defined as:

$$L_W = 10 \log_{10} W/W_0 (\text{dB}\, re\, W_0) \tag{2.5}$$

   where W is the sound power (W) and W_0 is the reference sound power, standardized at 10^{-12} W, corresponding to the reference pressure of 20 µPa (2×10^{-5} N/m^2).

   The relationships between the sound power and sound power level are given in Table 2.1, from which it can be seen that power ratio < 1 lead to negative levels. Different international standards describe methods for determining the sound power levels of noise sources (see Annex 4).

5. *Sound intensity level* noted *IL* or L_{I} (dB) is the measure of the acoustical disturbance produced at a point removed from the source and is defined as the ratio of two sound sources intensities, I_1 and $I_2 = I_{\text{ref}}$ expressed in logarithmic form as:

$$IL = L_{\text{I}} = 10 \log_{10} \frac{I_1}{I_{\text{ref}}} \tag{2.6}$$

   where I_{ref} is the reference intensity of 10^{-12} W/m^2 (if the reference is different, one must note explicitly the reference value). The sound intensity level depends on the distance from the source and the losses in the air path (ISO 3740, ISO 3744; see Annex 4).

Table 2.1. Sound power level (dB) and sound radiated power (W) in linear, exponential and dB-log scale (data from Beranek 1960, 1992)

Sound radiated power (W)		Sound power level (L_w, dB)	
Usual notation	Exponential notation	Relative to 1 W	Relative to 10^{-12} W
100 000	10^5	50	170
1,000	10^3	30	150
100	10^2	20	140
10	10^1	10	130
1	1	0	120
0.1	10^{-1}	−10	110
0.01	10^{-2}	−20	100
0.001	10^{-3}	−30	90
0.00001	10^{-5}	−50	70

6. *Sound pressure level* noted SPL or L_p (dB) is the ratio between the effective measured sound pressure and the sound pressure at a source reference:

$$L_p = 10 \log_{10} \frac{\overline{p^2(t)}}{p_{ref}^2} = 20 \log_{10} \frac{p_{rms}}{p_{reference}} \tag{2.7}$$

where $p_{reference}$ is the reference pressure of 20 µPa (2×10^{-5} N/m^2), for sound propagation in air, since it corresponds to the rms pressure of a pure tone at 1 kHz, which is just audible by the human ear. The rms corresponds to the acoustic pressure fluctuations of the acoustic wave and is given by the equation:

$$\overline{p^2(t)} = \underline{\lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} p^2(t)\,dt} \tag{2.8}$$

where T is the averaging time, very large compared to the period of pressure fluctuation and should extend to infinity for random fluctuations, whose statistical properties remain stationary with time. Since this parameter has the dimensions of pressure squared, the label "root mean square" was associated with this fluctuation. The parameter p_{rms} is given by the square root of the mean square pressure. In practice the range of variation of p_{rms} is very large, from 10^{-5} Pa to 10^3 Pa. For this reason, the logarithmic scale is always used.

Typical values of the rms pressure fluctuation and the corresponding sound pressure levels are given in Table 2.2.

The sound pressure level at different frequencies produced by different sources (wind, cars, train, etc.) is given in Table 2.3.

Table 2.2. Typical rms pressure fluctuations and their sound pressure levels (Fahy and Walker 1998, with permission)

Source	Pressure fluctuation p_{rms} (Pa)	Sound pressure level L_p (dB *re* 2×10^{-5} Pa)
Jet engine at 3 m	200	140
Pneumatic hammer at 2 m	2	100
Conversational speech	0.02	60
Residential area at night	0.002	40
Rustling of leaves	0.0002	20
Threshold of hearing	0.00002	0

Table 2.3. Noise data at octave-band center frequency for different noise sources (Egan 1988)

Source	Sound pressure level (dB) at various frequencies (Hz)								SPL
	63	125	250	500	1,000	2,000	4,000	8,000	dB
Birds at 33 m	–	–	–	–	–	50	52	54	57
Cicadas	–	–	–	–	35	51	54	48	57
Large dog at 17 m	–	50	58	68	70	64	52	48	72
Lawn mower at 1.7 m	85	87	86	84	81	74	70	72	86
Pistol shot at 82 m	–	–	–	83	91	99	102	106	106
Surf at 3 m, moderate sea	71	72	70	71	67	64	58	54	78
Wind in trees, 16 km/h	–	–	–	33	35	37	37	35	43
Large trucks	83	85	83	85	81	76	72	65	86
Passenger cars	72	70	67	66	67	66	59	54	71
Motorcycle	95	95	91	91	91	87	87	85	95
Snowmobile	65	82	84	75	78	77	79	69	85
Train at 33 m	95	102	94	90	86	87	83	79	94
Car horn at 5 m	–	–	–	92	95	90	80	60	97
Commercial turbofan airplane	77	82	82	78	70	56	–	–	79
Military helicopter	92	89	83	81	76	72	62	51	80

The relation between sound pressure in microPascals and sound pressure level in decibels (re 20 μPa) for various sources of noise is given in Fig. 2.1. All confusion between sound power level (often expressed in Bels) and sound pressure level (expressed in dB) must be avoided. The former corresponds to the measure of the acoustic power radiated by the source and the later depends on the power of the source, the distance from the source and the acoustical characteristics of the space surrounding the source.