4 Noise Attenuation with Plant Material

4.1 Physical Aspects of Noise Attenuation by Vegetation

Outdoor sound propagation may range from a relatively simple to a very complex phenomenon, depending upon the nature of the source and the distribution of the surrounding area. To understand outdoor sound propagation and the transmission of sound and noise with plant material, it is necessary to study the complex acoustic climate of a plant community. The influence of a particular soil surface on sound propagation and the influence of overgrowing plant organs like stems, branches, twigs and foliage on the sound field inside vegetation are equally important. It is generally admitted that plants can attenuate sound by reflecting and absorbing energy in the viscous and thermal boundary layers near the plant surface, or by internal damping of sound-driven oscillations of branches or stems (Embelton 1963; Kragh 1979; Aylor 1977; Martens 1980; Bullen and Fricke 1982).

Figure 4.1 synthesizes the factors influencing noise attenuation in a forest stand through absorption, dispersion, reflection and refraction. Noise attenuation in its totality is composed of normal attenuation and excess attenuation.

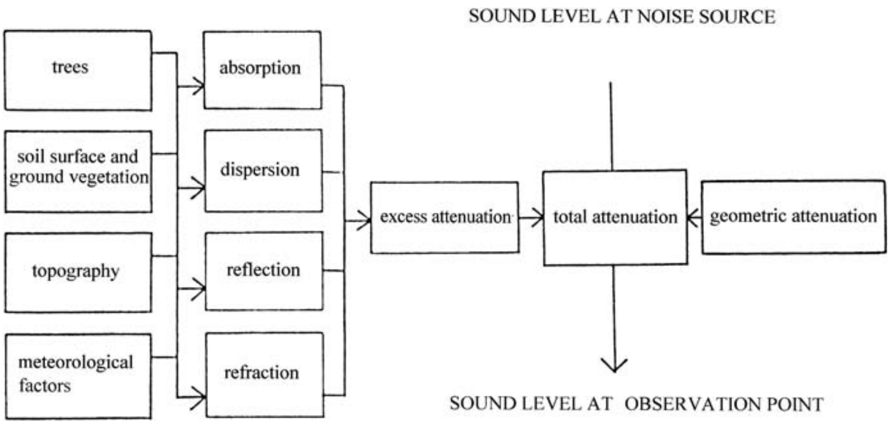


Fig. 4.1. Contribution of several factors (trees, soil, topography, meteorology) to total noise attenuation in a stand (Kellomäki et al. 1976)

Normal attenuation is due to spherical divergence and air absorption (Herrington 1974; Embelton 1996). Normal noise attenuation increases with distance, producing the well known "distance effect". As noted by Embelton (1966): "at twice the distance from the source, the surface of the wave front is four times as large, and the sound pressure level decreases by 6 dB. For a line of sources (e.g. a line of cars along a road), the sound wave spreads cylindrically in two dimensions. In this case, the sound pressure level decreases by 3 dB per doubling of distance, which is the half-rate for spherical spreading".

Furthermore, reflection, refraction, scattering and absorption effects due to any obstruction (barriers, ground, vegetation, trees, hills, etc.) between noise source and receiver result in excess attenuation (Fang and Ling 2003).

The attenuation of outdoor propagation sound (Bies and Hansen 1996) can be determined by the following four steps:

- the determination of the sound power level (L_W) of all sources;
- the calculation of the individual components of excess attenuation for all sources;
- the computation of the resulting sound pressure level at selected points in the environment for each of the individual sources;
- the computation of the predicted sound pressure level produced by all of the individual sources at selected points in the environment.

Attenuation by a tree belt, defined as the intensity at its far edge, relative to the intensity I_0 which is the intensity of *a plane wave incident* on it from one side, depends firstly on the scattering cross-section and absorbing cross-section of individual trees, secondly on the number of trees per square meter and thirdly on insertion loss. If the first and second factors can be easily understood, the insertion loss needs more comment, related to the nature of the ground – soft or hard. If the ground is acoustically soft, due to interference between direct and ground-reflected waves, significant attenuation of low frequencies may occur in the absence of vegetation. Over hard ground, the phenomenon is different; and the sound level can be locally increased due to consecutive interference. This effect would be destroyed by vegetation, since the phases of waves arriving at a point on the far side of the belt would be random (Bullen and Fricke 1982).

If the *incident wave is not plane* but arises from a source at a finite distance from the belt, it would normally undergo spherical spreading, which would also be disturbed by the presence of vegetation.

Scattering phenomena in the horizontal plane are very different from scattering in the vertical plane. In the horizontal plane, the wave undergoes a number of scattering events before leaving the vegetation; and it is possible to imagine that a wave which is scattered at a large angle to the horizontal will leave the vegetation without further scattering. In the vertical plane, scattering through the "top" of the vegetation is different from that on the "bottom" near the ground.

Empirical relationships were established between excess attenuation, frequency and distance of sound traveling through a heavily wooden area. In 1961, Hoover, cited by Bies and Hansen (1996), recommended the following equation:

$$A = 0.01 r f^{\frac{1}{3}} \tag{4.1}$$

where r is the distance (m) and f is the frequency (Hz).

As regards the attenuation of a tree belt and vegetation of different sizes – length and width – it appears that about 3 dB excess attenuation (over the infinitely long belt case) may be gained by making the belt approximately as wide as it is deep (Bullen and Fricke 1982). Scattering from the side of the belt can of course be observed, but much greater gains in attenuation than this will probably not be possible, since diffraction around the belt will become more important when the belt becomes narrower.

4.2 Ground Attenuation

A typical forest surface is a multi-layer structure, containing much decayed plant matter, such as leaves, needles, branches, decayed trunks and loose soil. Forest soils may be classified, in most cases, as acoustically soft (Martens et al. 1985). Three type of acoustic wave can propagate through or near the ground: plane waves, spherical waves and surface waves. If the propagation phenomena of plane waves and spherical waves are relatively easy to understand, the surface wave propagation requires some explication. The surface wave has a direction of propagation, which is parallel to the porous ground surface, and a direction of polarization associated with the elliptical motion of air particles as the result of combining motion parallel to the surface with that normal to the surface in and out of the ground.

When sound travels from the source to the receiver, close to the ground, an interaction is observed between the direct sound and the sound reflected from

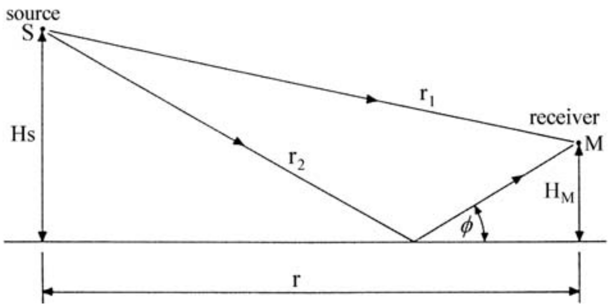


Fig. 4.2. Sound propagation path above a flat absorbing ground (Attenbourg 1988). Reprinted with permission from Elsevier, copyright 2005

the ground, as can be seen in Fig. 4.2. As noted by Reethof et al. (1977), the effect of the ground on sound absorption is due to the important porosity of the forest surface and to the interference between the ground-reflected wave and the direct wave. This interference forms a coherent source some distance above the ground, producing a "cancellation" effect. The ground-reflected wave has to travel a longer distance than the direct wave, so that there will be a location at a certain distance from the source where the two waves are exactly at opposite phases, bucking one another. Because of the porosity of the ground, the reflected wave, as it leaves the ground, will be at a somewhat different phase than the incident wave at the ground surface. Compared with the incident wave, the phase of the reflected wave is retarded by the delay, due to the increased distance travelled by the reflected energy and of course by the soil porosity. If the interaction between the sound and the ground is to be measured, the first request is to note the dependence of experimental data on source – receiver geometry.

The relationships between the shape and length of ground on sound propagation and the attenuation spectrum were reported over the years (Ingård 1953; Martens 1977; Reethof et al. 1977; Martens et al. 1985; Wempen 1986; Attenborough 1988; Embelton 1996).

The most important ground physical parameters studied were:

a) *the porosity* (expressed in %).
b) the *normalized characteristic impedance* (defined as the ratio of the pressure and normal velocity at the surface of a semi-infinite medium divided by the characteristic impedance; product of density and velocity). The real part of ground impedance is called "resistance" and the imaginary part is called "reactance" (Attenborough 1992).
   Wempen and Mellert (1990) suggested an empirical model for ground impedance (Z), written in terms of frequency (f) and *relative admittance* (β):

$$\beta = \frac{1}{Z} = 0.012 + 0.006\mathrm{i} + 60f \exp\left[-\mathrm{i} \arctan\left(\frac{0.003}{f}\right)\right] \tag{4.2}$$

c) the *flow resistivity*, σ, when knowledge of the propagation constant of sound within the ground layers is required. In the next lines, several values of effective flow resitivity, for different grounds, are given:
   - the pine forest $\sigma_e/1{,}000 = 7.5$ in a frequency range of 0.05 kHz to 7.5 kHz;
   - new snow $\sigma_e/1{,}000 = 5.5$ in a frequency range of 0.1 kHz to 5.0 kHz;
   - wet sandy loam $\sigma_e/1{,}000 = 4{,}546$ in a frequency range of 0.1 kHz to 2.0 kHz;
   - grassland $\sigma_e/1{,}000 = 3{,}000$ at 2,500 Hz (Attenbourg 1988);

   More detailed data on flow resistivity and porosity are given in Table 4.1.

Table 4.1. Measured values of flow resitivity (R_s) and corresponding porosity for different soils (Martens et al. 1985). Reprinted with permission from the Acoustical Society of America, copyright 2005

Surface	Soil layer	Flow resistivity (R_s; 10^3 Pa s m^{-2})	Porosity (%)
Lawn	R, layer with roots	237 ± 77	50.5 ± 9.3
Bare sandy plain	A, mineral soil	366 ± 108	36.2
Soil layer with roots	R, layer with roots	114 ± 53	55.2 ± 4.5
Grass covered soil	R, layer with roots	189 ± 91	–
Beech forest	L, litter layer	22 ± 13	82.3 ± 1.9
Pine forest	L, litter layer	9 ± 5	67.5 ± 4.1
Mixed forest with	L/F, litter/fermentation layer	13.3 ± 3.0	–
beech and pine	F/H, fermentation/humus layer	52 ± 24	76.3 ± 3.2
	H, humus layer	210 ± 93	–
	A, mineral soil layer	102 ± 60	54.7 ± 6.8
Mixed deciduous forest	L/F, litter/fermentation layer	30 ± 31	–
with oak and beech	H, humus layer	375 ± 69	84.6 ± 5.6
	A, mineral soil layer	540 ± 92	51.5 ± 4.8

d) *the ground surface admittance*:
The modelling of sound propagation over a finite impedance ground proposed by Attenborough (1988) takes into consideration the pressure reflection coefficient which, for a plane wave is:

$$R_p = |R_p| \exp(i\varphi) \tag{4.3}$$

where φ represents the phase change on reflection.
The total pressure at the receiver is given by:

$$P_t = P_d + R_p P_r \tag{4.4}$$

where P_d is the direct contribution and P_r is the speculary reflected contribution.

As noted by Attenborough (1988) "for a given source – receiver geometry, the two contributions P_d and P_r will lead to minima in the total pressure at frequencies where they interfere destructively or, in other words, when the phase difference between them is an odd number of φ radians (180°). The phase difference is caused both by path length difference and by the phase change φ on reflection at the ground, so r_1 is the length of the direct ray from the source to receiver, and r_2 is length of the reflected ray."

The condition for minimum in the total pressure is:

$$(2n+1)\pi = \frac{2\pi}{\lambda}(r_2 - r_1) + \phi \tag{4.5}$$

where λ is the wavelength, or the frequency (f_m) is:

$$f_m = c_0[(2n+1)\pi - \phi]/[2(r_2 - r_1)] \tag{4.6}$$

The extreme ground conditions are, for an acoustically *hard boundary*, for which we have $\phi = 0$ and a pressure-release boundary, for which $\phi = \pi$. For the former case, the frequency of the first (f_h) and subsequent minima is given by the equation:

$$f_h = c_0(2n+1)/[2(r_2 - r_1)] \tag{4.7}$$

where $n = 0, 1, 2, 3, ...$ and c_0 = velocity of sound in air.

The frequencies of the associated pressure minimum (f_{pr}) for a pressure release boundary are given by the equation:

$$f_{\mathrm{pr}} = nc_0/(r_{\acute{e}} - r_1) \tag{4.8}$$

If the *ground is porous*, it will have finite impedance and φ will be non-zero $\phi \neq 0$.

From (4.7), it can be stated that the resulting pressure minimum will occur at lower frequencies than those predicted for an acoustically hard boundary. The first minimum, called by Attenborough (1988) the *ground effect dip*, depends strongly upon the acoustical characteristics of the ground and relatively little upon the source – receiver geometry. In this theoretical approach, it was stated that the sound wave is plane and the sound field was produced by a point source.

In practical outdoor situations, the waves are spherical. In this case, two main aspects must be considered. Firstly, in the near field, the pressure due to a point source above an absorbing plane is inversely proportional to distance from the source and, secondly in the far field, the pressure is inversely proportional to the square of the distance.

As regards the relationships between sound frequency and distances, it can be noted that, for "frequencies less than 300 Hz and for ranges greater than 50 m over typical grassland, a surface wave, decays principally as the inverse square root of the horizontal range and exponentially with height above the surface. At grazing incidence, the condition for its existence is simply that *the imaginary part* of the ground impedance (*the reactance*) is greater than the *real part* (*the resistance*)" (Attenborough 1992).

For grass-covered and forest soils (Martens et al. 1985), the real part of the acoustic impedance is relatively independent of frequency, while the imaginary part strongly decreases with frequency, as can be seen from Fig. 4.3, in which different type of forests (mixed deciduous, pine forest, beech forest) and soils (intact soil, sandy soil, ivy underground) are studied.

A deep insight on the properties of forest soils has been obtained by performing laboratory tests on soil samples (Reethof et al. 1977), using an adapted

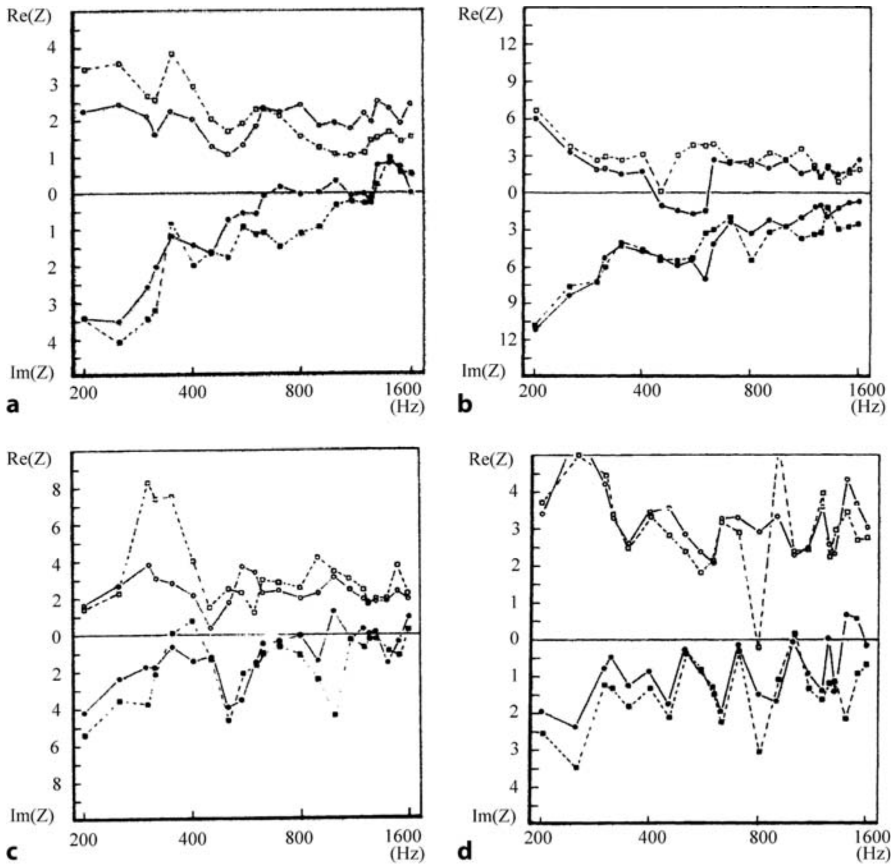


Fig. 4.3. Real and imaginary parts of the acoustic impedance versus frequency in different forests (Martens et al. 1985). Reprinted with permission from the Acoustical Society of America, copyright 2005. **a** Pine forest compared with intact soil (*circles*), **b** fir forest, **c** beech forest, **d** elm forest

standing-wave tube. Figure 4.4 shows a typical curve of the absorption coefficient (α) of a sample of forest soil as a function of frequency. A primary peak was observed at 250 Hz and a maximum value at 1,000 Hz, between them a dip low value at 500 Hz. Note the very good repeatability of the acoustical measurements.

Ground porosity variation induced by the contribution of the leaf layer in a deciduous forest is shown in Fig. 4.5. The absorption coefficient increases with increasing frequency. Compared with grass, the leaf layer determines about 20% of the increase in the absorption coefficient.

Analyzing previous data and comparing them with the noise spectra of trucks and automobiles, which are fairly flat with peaks in the 125-Hz octave

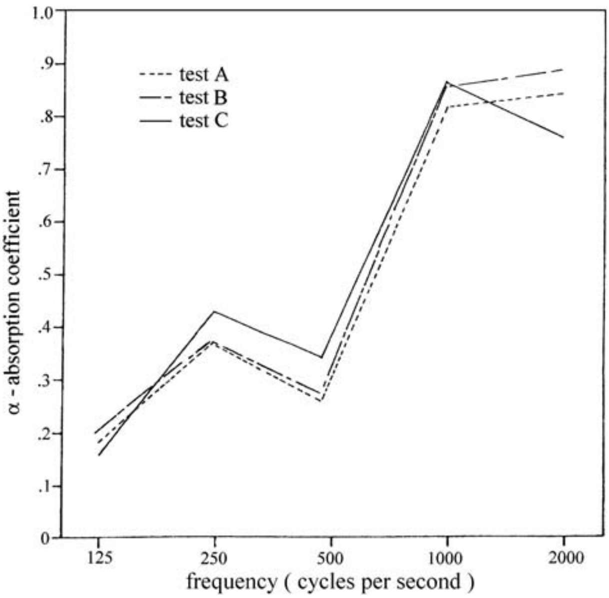


Fig. 4.4. Absorption coefficient of a normal incidence sound by a sample of forest floor, as a function of frequency (Reethof et al. 1977)

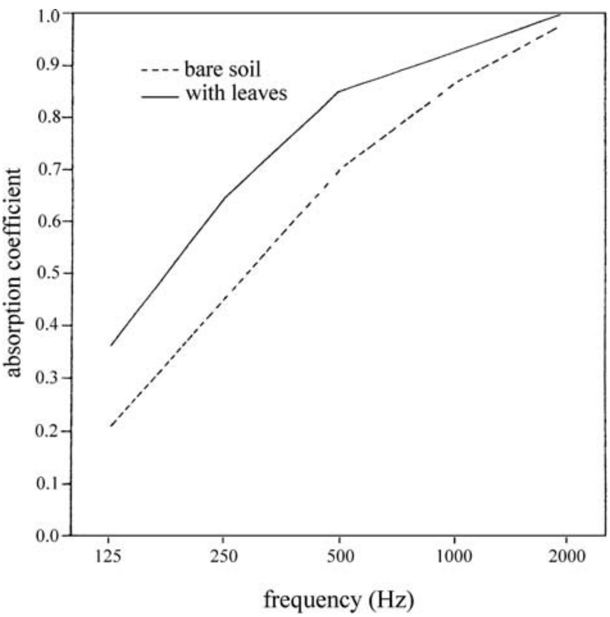
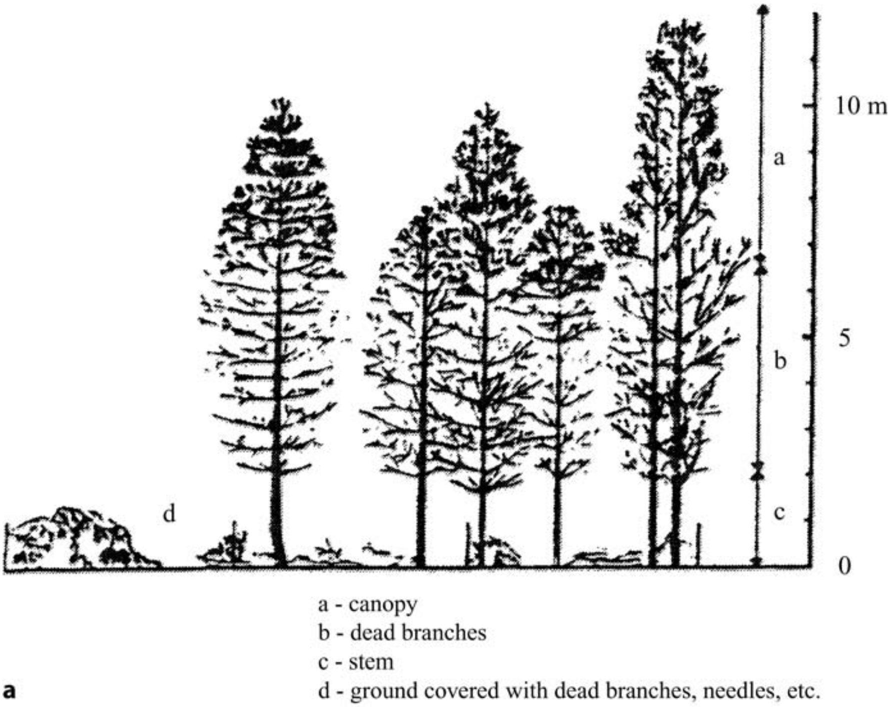
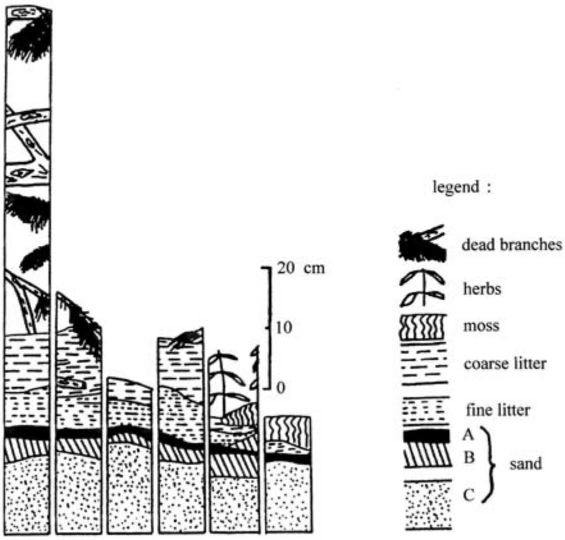


Fig. 4.5. Absorption coefficient at normal incidence sound for a soil sample with leaf litter from a deciduous forest compared with a bare soil, as a function of frequency (Reethof et al. 1977)

band, it can be noted that increasing absorption at frequencies higher than 500 Hz, allows one to imagine that several hundred meters of tree belt width are required to produce an important reduction in the A-weighted sound levels from the traffic.



a



b

Fig. 4.6. Typical structure of a *Pinus nigra* monoculture stand locate on a soil including dead and living covering material (Huisman and Attenborough 1991). Reprinted with permission from the Acoustical Society of America, copyright 2005. **a** Profile of the vegetation structure, **b** soil structure

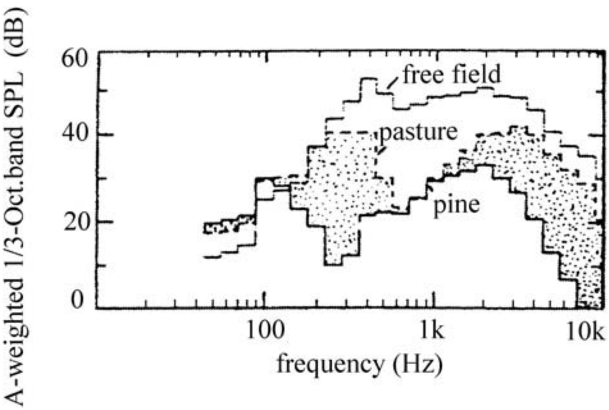


Fig. 4.7. Immission spectra of traffic noise for free field, pasture and pine stand for traffic noise for the following parameters: line source height 0.75 m, source length 600 m, receiver height 1 m, distance from source axis 100 m, effective flow resistivity (σ_e) for the pasture 125,000 N s m^{-4}, excess attenuation α 0 m^{-1}; and, for the pine stand σ_e 7,500 N s m^{-4} and α 25 m^{-1} (Huisman and Attenborough 1991). Reprinted with permission from the Acoustical Society of America, copyright 2005

Results of theoretical and "in situ" studies (Huisman 1990; Huisman and Attenborough 1991) of the effect of forest ground on the A-weighted imission level of road transmission noise, on a typical configuration of a planted pine forest (Fig. 4.6a), with a characteristic soil stratification (Fig. 4.6b) are shown in Fig. 4.7. This figure displays three immission spectra for free field, pasture and pine stand, calculated from a line source with road traffic situated at 100 m. The pine stand spectrum is lower for almost all frequencies, compared with pasture or free field. The total A-weighted immission spectrum in this pine stand is reduced by 9.9 dB, compared with pasture.

The soft forest floor has a big influence on low-frequency noise (< 500 Hz). The effective flow resistivity (σ_e) for the pasture was σ_e = 125,000 N s m^{-4} and the excess attenuation was α = 0 m^{-1}; and for the pine stand, σ_e = 7,500 N s m^{-4} and α = 25 m^{-1}.

In the studied pine stand, the ground effect seems evident and can be easily observed from the spectrum zone corresponding to low-frequency propagation.

4.3 Scattering by Trees

A simple calculation of the wavelength of a sound wave of 1,000 Hz frequency interfering with trees in a forest shows that the wavelength is comparable with tree diameter (e.g. $\lambda = 33$ cm for a sound velocity of 330 m/s). The incident acoustic waves are partially reflected and refracted, producing a typical scattering phenomenon, as shown in Fig. 4.8. The acoustic scattering and attenuation of sound are studied mainly along a line between a source and a receiver. The branches and the foliage partially scatter the incident acoustic energy to the side and backwards, producing a shadow zone behind the vegetation. The canopy of deciduous trees attenuates the incident noise. Plants in general and trees in particular can attenuate the sound by reflecting and absorbing energy in the viscous and thermal boundary layers near the plant surface or by internal damping of sound-driven oscillations of branches or stems (Aylor 1972a, b, 1977).

Scattering effectiveness is consistent with the geometry of scatterers such as trunk, branch and leaves (Huisman 1989). The bigger the scatterer, the lower the frequency at which the scattering phenomenon becomes effective. Scattering increases with frequency and the transmission path become more and more complex, producing absorption of acoustic energy. At low frequencies, this phenomenon is absent, because the wavelength is large compared to the diameter of trunks and branches; and the acoustic energy is transmitted easily. The propagation of sound through a large number of scatterers (trunks of

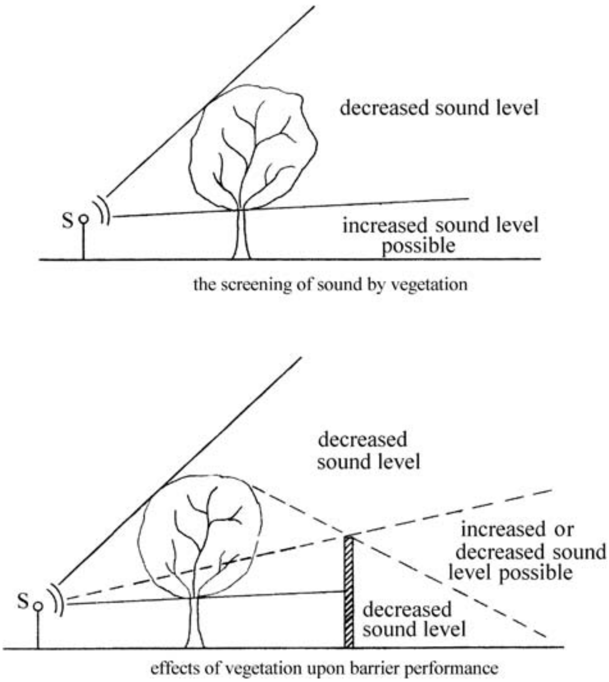


Fig. 4.8. Screening of sound by a tree (Lyon et al. 1977)

trees), in a first approximation, can be treated as a classic diffusion problem if the depth of the tree belt is large and the absorption is relatively low (Bullen and Fricke 1982). It was deduced that about 3 dB excess attenuation may be gained if the belt is as wide as it is deep. It was noted (Huisman 1989, 1990; Huisman and Attenborough 1991) that the interaction between trunk scattering and ground effect is much more complicated than the diffraction theory and more sophisticated modelling is necessary for a complete understanding of the experimental data produced by in situ measurements. Modelling the complex shapes of trees requires a reduction to simple shape components, such as cylinders, planes or spheres, for which analytical solutions for sound scattering are available, avoiding the application of numerical techniques that are expensive.

Figure 4.9 synthesizes the main dendrological and physical characteristics of the stand effecting excess attenuation in a tree belt. These characteristics are: the biomass of the stand, the structure of the stand in a horizontal plane (size and shape of the canopy) and the quality of the surfaces (size and shape of leaves and needles, soil). These characteristics allow admitting that mixed stands composed of coniferous and deciduous trees and bushes would be the most effective for noise attenuation.

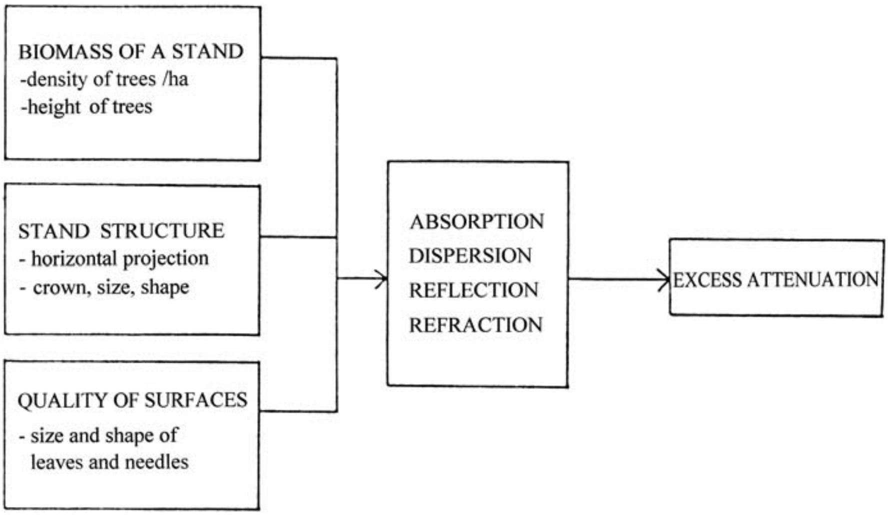


Fig. 4.9. Excess attenuation, absorption, dispersion, reflection, refraction and stand characteristics (Kellomäki et al. 1976)

4.3.1
Scattering by Stems

Because of the high complexity of acoustic scattering phenomena, Rogers et al. (1990) proposed theoretical studies, in an anechoic chamber, using models (wooden cylinders with limbs) to reproduce tree architecture (Fig. 4.10). It was noted that, at a fixed frequency, the optics scattering approximation can be applied to this acoustical study, if the illumination of the surface of the scattering solid by the source is correct and if this surface is the principal contributor to the total scattering.

Supposing a point source with acoustic strength A, placed at 1 m from the cylindrical specimen. The insonification of the cylinder $A_{(r)}$ can be calculated using the spreading factor:

$$A_{(r)} = A/r \exp(-\mathrm{i}kr) \tag{4.9}$$

where r is the distance from the source to the point of interest on the cylinder and k is the wave number.

The back-scattered sound intensity at any point in space is found interacting over the illuminated zone of the cylinder, which is visible to the receiver. Each surface element becomes a source characterized by its amplitude, phase and geometric spreading factor.

Rogers and Lee (1989) analyzed the case of scattering from short cylinders (Fig. 4.11) normally illuminated and at 15° with respect to normal to the cylinder axis. As can be seen from this figure, the scattering pattern varies significantly with scatter angle; and the scattering is most important when the incident angle with respect to the cylinder axis equals the scattering angle. It was stated that these patterns are the radiation patterns of a line source with appropriate length and intensity. The maximum back-scattered acoustic signal occurs for signals incident normal to the axis of the cylinder. When this is not the case, the signal is considerably weaker.

Figure 4.12 displays the signals at the microphone and the back-scattered signal measured in an anechoic chamber for a trunk of 1 m length and 5 cm diameter, supporting six limbs of 0.4 m length and 2.5 cm diameter, as shown

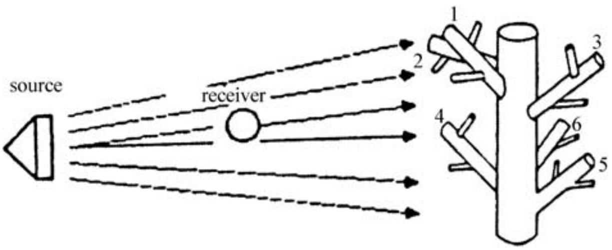


Fig. 4.10. Tree simulation for back-scattering measurements with cylindrical samples with limbs (Rogers et al. 1990)

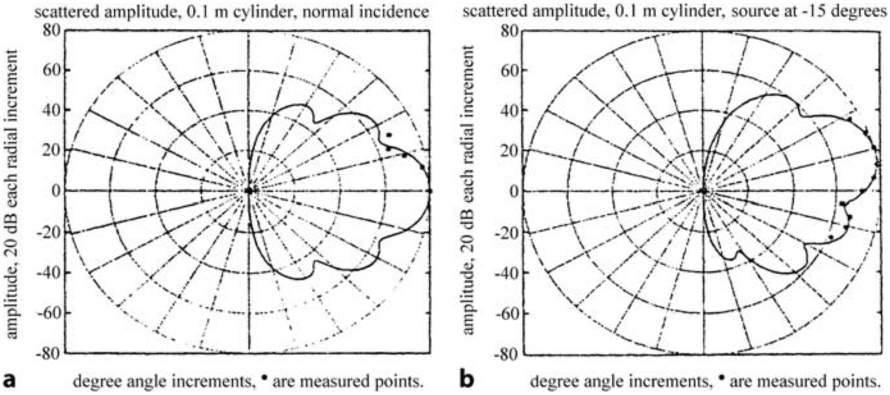


Fig. 4.11. Scattered amplitude from a cylinder of 0.1 m length. **a** source at normal incidence; **b** source at 15° (Rogers and Lee 1989)

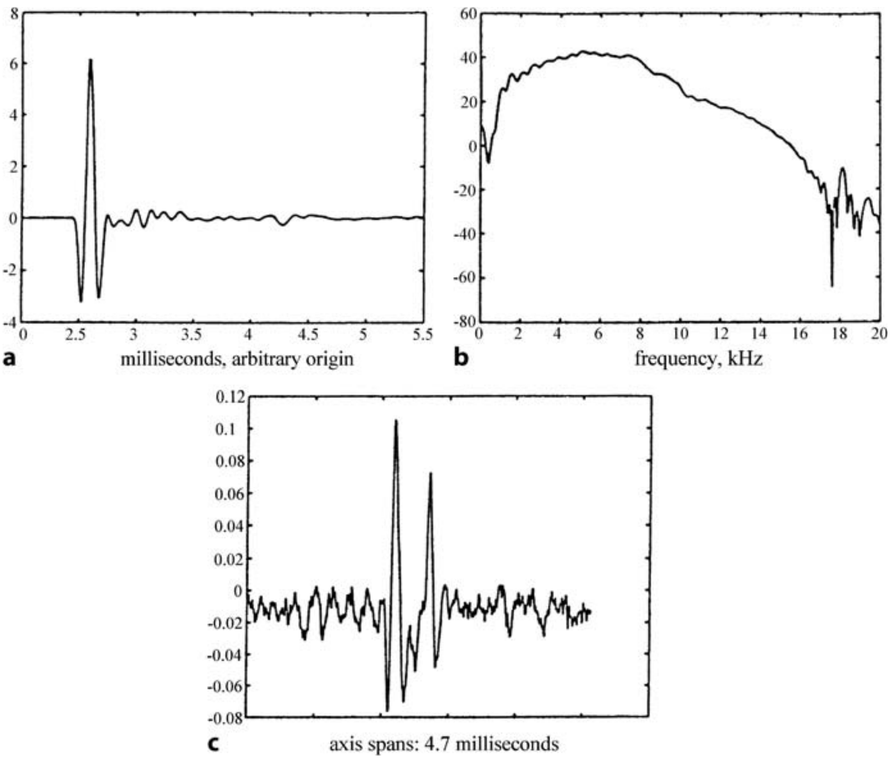


Fig. 4.12. Comparison between the emission signal and the back-scattering signal from one sample, in anechoic chamber (Rogers et al. 1990). **a** Direct signal at the microphone (amplitude in V); **b** corresponding spectrum (dB); **c** the back-scattering signal from the tree in a single direction (amplitude in V)

previously in Fig. 4.10. The useful bandwidth of the direct pulse was between 1 kHz and 12 kHz.

The next step in this approach was to study the back-scattering signals from tree samples arranged in a “grove” (Fig. 4.13). The corresponding spectra are given in Fig. 4.14. The frequency domain response of a single artificial tree from the grove is shown in Fig. 4.14a. and corresponds to the range 1 – 18 kHz. The responses of the nine artificial trees from the grove are shown in Fig. 4.14b, c. Both time and frequency domain signals are very complex, showing a high variability, which can be explained by the multiple returning pulses from different trees and from different zones of individual trees.

As far as the experimental data in the anechoic chamber with artificial trees seems to be coherent, it is therefore natural to consider the study of a natural tree belt. In this case, the ground adds more complexity to the interpretation of the experiments. Rogers et al. (1990) used a Freon horn source and a sound level meter located at 40 m and 60 m along a line normal to the edge of tree belt; and there was some cultural noise, automobile traffic and a temperature of 11 °C. Unfortunately in this report, there was no information about tree species and other practical parameters. Short blasts of the horn and the corresponding back-scattered signals were recorded (Fig. 4.15). The direct pulse spectrum is shown by the upper line, with the useful bandwidth between 0.5 kHz and 5.0 kHz. A big variability in the amplitude of the scattered signal is observed. The region between 2,500 Hz and 3,000 Hz displays less apparent attenuation than the region between 1,300 Hz and 1,800 Hz and between 3,300 Hz and 3,600 Hz. The spectral amplitude of the scattered signal is 30 dB below that of the direct signal from the tree belt. “If one assumes geometrical spreading, while ignoring ground effect, and uses the edge of the woods to approximate the spreading effect of the scattered signal, one would predict 14 dB reduction for the signal of a perfect back scatterer” (Rogers et al. 1990). The estimated scattering cross-section was 16 cm, which probably roughly corresponds to the tree diameter. In the case of the grove of trees, the ground effect does not exist and a simple geometric spreading predicts 15 dB attenuation.

Attenuation measurements in two pine plantations (labeled good and poor) were reported by Leonard and Herrington (1971). The dendrological charac-

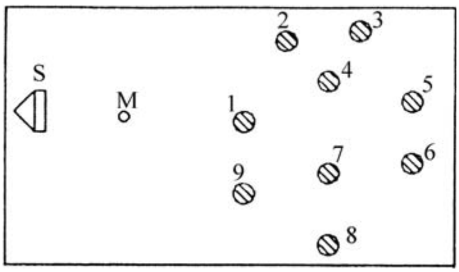


Fig. 4.13. Tree samples arrangement in a “grove” in an anechoic chamber for the simulation of a tree belt composed of nine trees. The source *S* and the microphone *M* is behind the trees (Rogers et al. 1990)

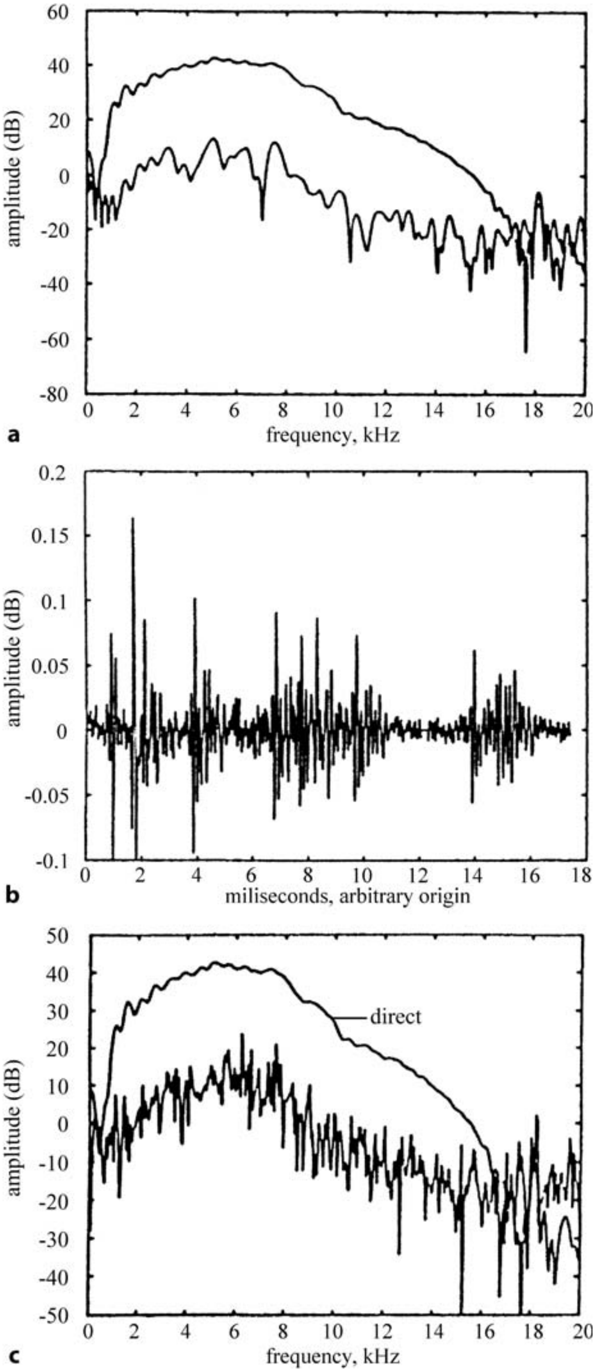


Fig. 4.14. "Grove" Spectra in frequency range 0–4,000 Hz (Rogers et al. 1990). In **a**, **c**: *upper* spectrum is direct signal, *lower* spectrum is scattered signals. **a** Spectrum of a single tree compared to direct spectrum (*upper*). **b** Synthetic scattering from nine trees grove in time domain. **c** Spectrum of the nine trees compared with direct signal spectrum

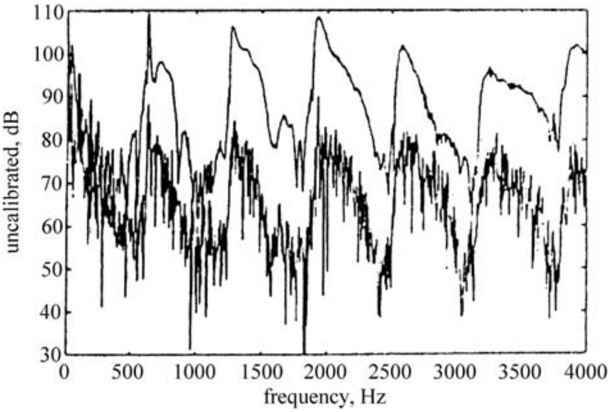


Fig. 4.15. Spectra for direct and scattered sound measurements on tree belt (Rogers et al. 1990). *Upper* spectrum is direct signal, lower spectrum is scattered signals

teristics of the trees are given in Table 4.2. The stem maximum diameter was between 11.2 cm and 12.7 cm and the maximum height between 12.6 m and 16.2 m. The sound pressure level was measured at different frequencies (125, 250, 500, 100, 200 Hz) and at different distances (2.6, 16.5, 33.0, 66.0, 82.0 m).

The excess attenuation displayed in Fig. 4.16 was calculated for different frequencies, with (4.10):

$$SPL_{r_2} - SPL_{r_1} = 20 \log \left(\frac{SPL_{r_1}}{SPL_{r_2}} \right) + A_{\text{excess}} \tag{4.10}$$

where r_1 and r_2 are the distances from the source.

The first term of this equation accounts for the reduction in the SPL in a free field, free from a boundary, for which a loss of 6 dB was measured. The second term includes the attenuating effect of atmospheric absorption, wind turbulence, temperature gradient, ground effect and trees. Very small differences were observed between the poor and good sites at 500 Hz. The "good site" produced more attenuation between 125 Hz and 500 Hz, while the "poor site" produced more attenuation between 500 Hz and 1,000 Hz.

Bullen and Fricke (1982) reported measurements in a reverberant room, on five young trees, about 2 m high. The absorption of the normalized cross-

Table 4.2. Dendrologic characteristics of the pine stand (Leonard and Herrington 1971)

Stand	Stem diameter (cm)		Height (m)		Height to live crown	Basal area
	Maximum	At 1.20 m	Maximum	minimum	(m)	(m^2/ha)
No. 1, good	12.7	10.9	16.2	13.4	8.4	35.0
No. 2, poor	11.2	7.4	12.6	7.9	4.9	16.6

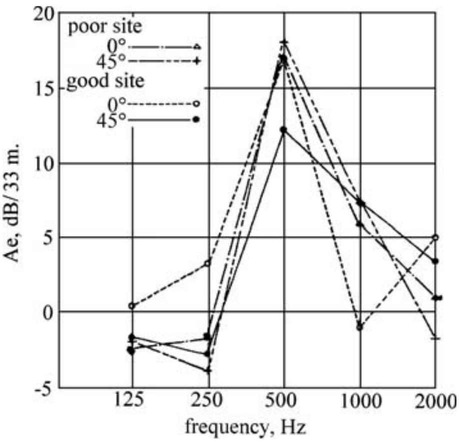


Fig. 4.16. Excess attenuation versus frequency (Leonard and Herrington 1971)

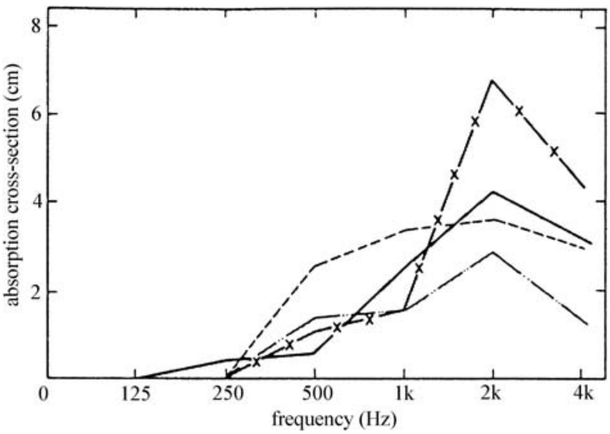


Fig. 4.17. Normalized absorption cross-section versus frequency for pine, maple, ash, magnolia young trees, 2 m height (Bullen and Fricke 1982). Reprinted with permission from Elsevier, copyright 2005

section (cm) versus frequency is shown in Fig. 4.17. At 2 kHz frequency, all species have a maximum absorption cross-section (e.g. for ash 6.5 cm, for pine 4.5 cm, for maple 2.8 cm).

Kellomäki et al. (1976) performed systematic measurements to study the influence of dendrological characteristics of trees on excess attenuation in several stands such as: pine, spruce and mixed (20% birch and other broadleaved species). The density of stems/ha was between 500 and 3,000. The sound source was placed at 12 m from the edge of the stand, reproducing a real situation. The attenuation coefficient was measured as a function of several parameters, such as the percentage of dominant trees, density of trees/ha, total stem number of dominating and dominated trees, basal area, volume, height, age of the stand (Fig. 4.18); and regression equations were calculated. Several of them are given below:

1. Attenuation coefficient P and percentage of dominant trees (p):
   $P = 0.696 - 0.0005$, (p) $r = -0.554$ (significant at 1%, variance explained 31%).
2. Attenuation coefficient P and percentage of self-pruned stems (p_{p}):
   $P = -0.144 + 0.192$, (p_{p}) $r = 0.609$ (significant at 1%, variance explained 37%).
3. Attenuation coefficient P and total stem number (log):
   $P = 0.903 - 0.064$, (log)$r = -0.653$ (significant at 1%, variance explained 43%).
4. Attenuation coefficient P and basal area:
   $P = 0.705 - 0.011$, (basal area) $r = -0.493$ (significant at 1%, variance explained 24%).
5. Attenuation coefficient P and height:
   $P = 0.389 + 0.003$, (height) $r = 0.535$ (significant at 1%, variance explained 30%).
6. Attenuation coefficient P and volume:
   $P = 0.615 - 0.0006$, (volume) $r = -0.291$ (significant at 5%, variance explained 8%).

The most important parameters able to explain the variance between 43% and 24% are: the total number of stems, percentage of dominant trees, percentage of self-pruned stems and the height. The volume which represents the major share of the biomass of the stand seems not to be an important parameter in sound attenuation in a stand.

The attenuation as a function of the density and height of trees is given in Table 4.3 for a spruce stand and Table 4.4 for a pine stand. In both cases, the attenuation increases with the increasing height of the trees.

Pal et al. (2000) performed measurements in stands planted around coal mines in India in order to protect the urban area from pollutants and noise. They derived linear regression relationships between the excess attenuation and tree density, average height, canopy branch, trunk diameter, vertical and horizontal light penetration. It was noted that light penetration, which depends on the leaf size, shape and density, is the most explicative parameter, while the density (number of trees/ha) has a<SNM>negligible effect. It was argued that sound waves propagate through the gaps between the trees, even with the maximum plantation density.

In this context of sound absorbers in the forest, it is natural to consider another important constituent of the trees, the bark. The acoustic properties of the bark of different species were studied by Reethof et al. (1977). The absorption coefficient (around 10%) was measured with a standard impedance tube. Small variations were observed between species. The quantitative contribution of the bark to the global behavior of a tree in the acoustical field is not known,

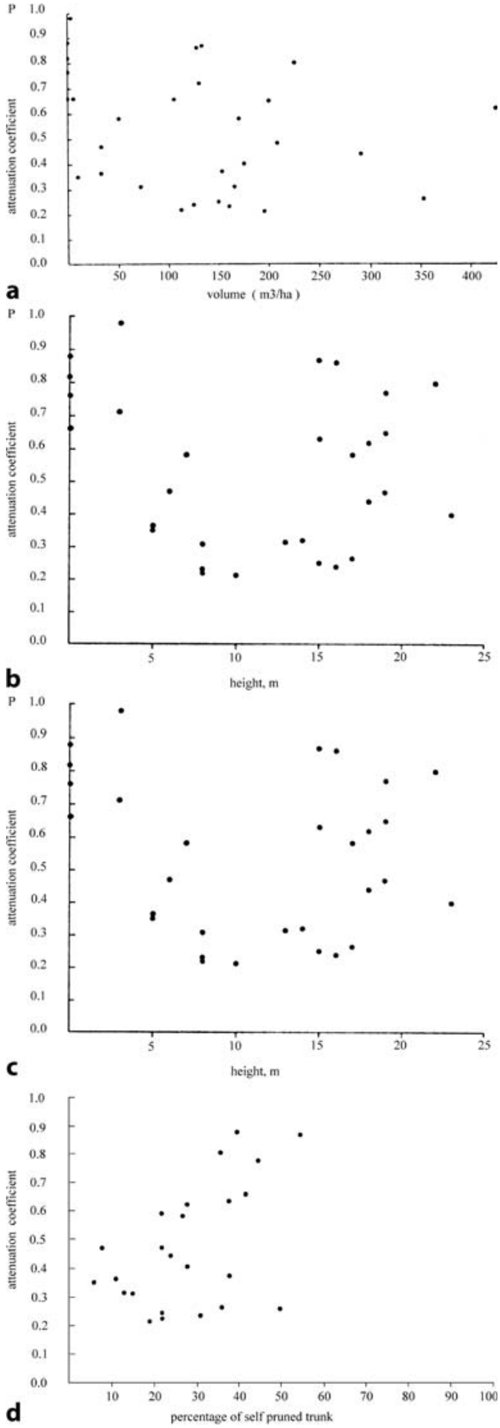


Fig. 4.18. Attenuation coefficient in spruce stand versus (Kellomäki et al. 1976) **a** Volume (m^3/ha), **b** height, **c** age of the stand, **d** percentage of dominant trees

Table 4.3. Attenuation coefficient as a function of density and height of a spruce stand (Kellomäki et al. 1976)

Density	Mean height of the trees (m)												
(stems/ha)	2	4	6	8	10	12	14	16	18	20	22	24	26
	Attenuation coefficient ($\times 10^{-3}$)												
250	715	643	587	547	523	515	523	547	587	643	715	803	907
500	638	566	510	470	446	438	446	470	510	566	638	726	830
750	594	522	466	426	402	394	402	426	466	522	594	682	
1,000	562	490	434	394	370	362	370	394	434	490	562		
1,250	538	466	410	370	346	338	346	370	410	466			
1,500	518	446	390	350	326	318	326	350	390				
1,750	501	429	373	333	309	301	309	333					
2,000	486	414	358	318	294	286	294	318					
2,250	473	401	345	305	281	273	281						
2,750	451	379	323	283	259	251							
3,000	441	369	313	273	249	241							

The attenuation coefficient P_i of the stand i is calculated as: $P_i = V_{ij} \times x_{ij}^2$. V_{ij} is the attenuation at the distance j in the stand i, and X_{ij} is the distance from the source to the point j in the stand i

Table 4.4. Attenuation coefficient as a function of density and height of a pine stand (Kellomäki et al. 1976)

Density	Mean height of the trees (m)												
(stems/ha)	2	4	6	8	10	12	14	16	18	20	22	24	26
	Attenuation coefficient ($\times 10^{-3}$)												
250	961	889	833	793	769	761	769	793	833	889	961	1,049	1,153
500	884	812	756	716	692	684	692	716	756	812	884	972	1,076
750	840	768	712	672	648	640	648	672	712	768	840	928	
1,000	808	736	680	640	616	608	616	640	680	736	808		
1,250	784	712	636	616	592	584	592	616	656	712			
1,500	764	692	636	596	572	564	572	596	636				
1,750	747	675	619	579	555	547	555	579					
2,000	732	660	604	564	540	532	540						
2,250	719	647	591	551	527	519							
2,500	707	635	579	539	515								
2,750	697	625	569	529									
3,000	687	615	559										

but it can be supposed that multiple scattering phenomena are influenced by the acoustical characteristics of the bark.

Modelling sound propagation in a forest is a challenging task (Attenborough 1985; Price et al. 1988; Attenborough et al. 1995). Application of scattering or diffusion theories (Embelton 1966; Barrière and Gabillet 1999; Salomons 2001;

Defrance et al. 2002; van Renterghem et al. 2002; Heimann 2003) has shown that some effects can be predicted. Defrance et al. (2002) found that, close to the trees, meteorological effects enhance the attenuation by the forest belt.

As a conclusion, it can be said that attenuation by the trunks of trees increases linearly with increasing trunk diameter. The increase in attenuation is weaker for higher tree densities. Trees can improve the efficacy of the barriers in downwind conditions. Trunk scattering diminishes the ground effect by reducing the coherence. The ground effect is important below 1,000 Hz. Above this frequency, attenuation by foliage is dominant. Forest reduces the vertical wind and temperature gradient and increases the acoustical efficiency in the case of favorable propagation conditions.

4.3.2 Scattering by Canopy and Foliage

The canopy, composed from branches and leaves, interferes with acoustic energy by scattering, refracting, reflecting and diffracting the acoustic waves. All these phenomena depend on sound wavelength and the dimensions of the boundary between zones of different characteristic impedance (Mueller and Kuk 2000). Smaller objects (like leaves) produce little refraction, diffraction or scattering of waves, but if the objects are numerous, the acoustical properties of the medium might be changed. The waves arriving at any point of the soundfield, after travelling by different paths depending on the geometrical complexity of surfaces and reflections, interfere constructively or not with the soundfield. Such interference between the incident and reflected waves establishes a spatial pattern which is typical for each site. This pattern depends on the speed of sound into the medium. Forest medium is a stratified medium, for which different surfaces act as wave guides, for example the space between the ground and the canopy (neither the ground, nor the canopy are totally absorbing). Temperature and wind gradients might also reflect sound waves, contributing to the formation of guides for sound propagation. The waveguide effect under the canopy or between strata of vegetation might explain the negative "excess attenuations" for certain frequencies or, in other words, this means that sound intensity decreases less than in proportion to the inverse square of the range. An effect of shadow zone for sound propagation during warm sunny days has been also observed.

As noted by Price et al. (1988), the absorption by foliage has been modelled as viscous plate drag, as the result of scattering absorption cross-section or as resonant absorption. Fricke (1984) noted that scattering rather absorption is the more important attenuating phenomenon in the midfrequency (around 1 kHz), while absorption becomes more dominant in the high frequencies. The effect of foliage is well illustrated in Fig. 4.19, in which two maximal attenuations are observed for summer time, the first maximum at about 200 Hz, corresponding to the ground effect, and the second in a high frequency at about 10 kHz, corresponding to the canopy, branches and foliage. The presence of more undergrowth and foliage in summer time explains the rapid increase in attenuation on frequencies higher than 1 kHz. Morton (1975) noted that, close to the ground, a "sound window" can appear which facilitates animal communication in forest (Fig. 4.20).

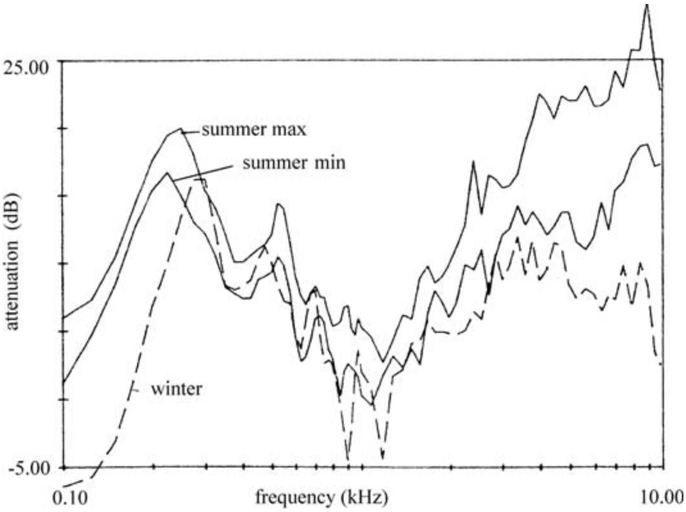


Fig. 4.19. Attenuation versus frequency in a forest stand composed from spruce and oak in alternating bands. Measurements in horizontal range of 72 m, receiver height at 1.2 m (Price et al. 1988). Reprinted with permission from the Acoustical Society of America, copyright 2005. The *continuous lines* correspond to summer measurements – maximum and minimum values; the *broken line* corresponds to winter measurements

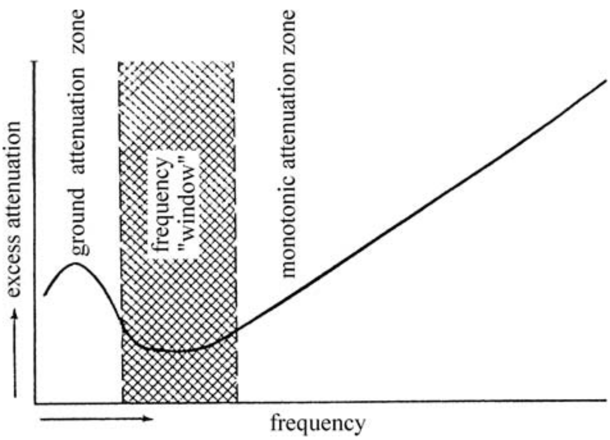


Fig. 4.20. Morton's frequency "window" as an idealized diagram showing the ground attenuation and the monotonic increase in attenuation (Marten et al. 1977)

To obtain a good understanding of the influence of the canopy on sound propagation and transmission through trees, it will be useful to investigate this phenomenon in two typical situations: first under well controlled acoustical conditions (anechoic and reverberant rooms) and second in situ, under natural conditions, for outdoor noise propagation.

4.3.2.1 Measurements in Anechoic Room

Studies in an anechoic room were performed by Martens (1980), selecting different species able to simulate three temperate forests and one tropical forest. The selected species for a temperate deciduous forest were: birch trees (*Betula* spp), having a diameter between 8 mm and 20 mm and a height of 2 m, hazel trees (*Corylus avellana*) of 1.10 m and privets (*Lignum vulgare*)

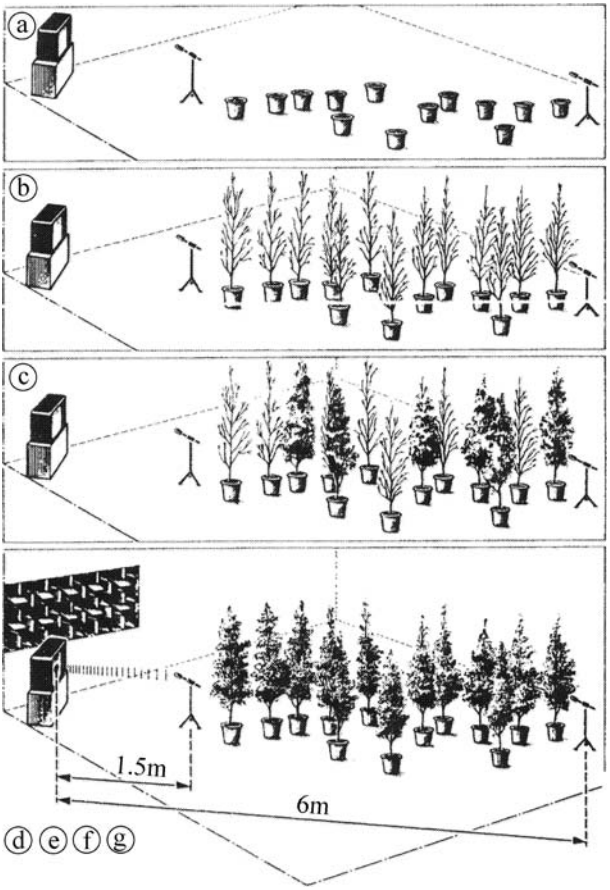


Fig. 4.21. Experimental arrangements of plants in the anechoic chamber (Martens 1980). Reprinted with permission from the Acoustical Society of America, copyright 2005. **a** Flowerpots filled with soil, **b** defoliated plants, **c** partially defoliated plants, **d-g** flowerpots in which the plants were grown

of 0.85 m. The model for the tropical forest was composed of samples from different families (Papilionaceaea, Rubiaceaea, Polygonaceaea, Vitaceaea, etc.) having a height of 2.30 m. The schematic view of the arrangement of plants in the anechoic chamber is given in Fig. 4.21. White noise of 105.5 dB sound pressure level was transmitted in the anechoic chamber, which had a working area of $4.5 \times 4.5\,m^2$. The total atmospheric absorption over 6 m between the source and the microphone at 10 kHz was 0.5 dB and was neglected. The results are shown in Table 4.5 and in Fig. 4.22. It is notable that the canopy of vegetation has a detectable influence on the noise field, at least in the frequency between 200 Hz and 10 kHz. The spectra in Fig. 4.22a and Fig. 4.22b show the influence of flowerpots filled with soil and root systems only and represent the "ground effect". Up to 8 kHz, no difference was detected. Figure 4.22c and Fig. 4.22g

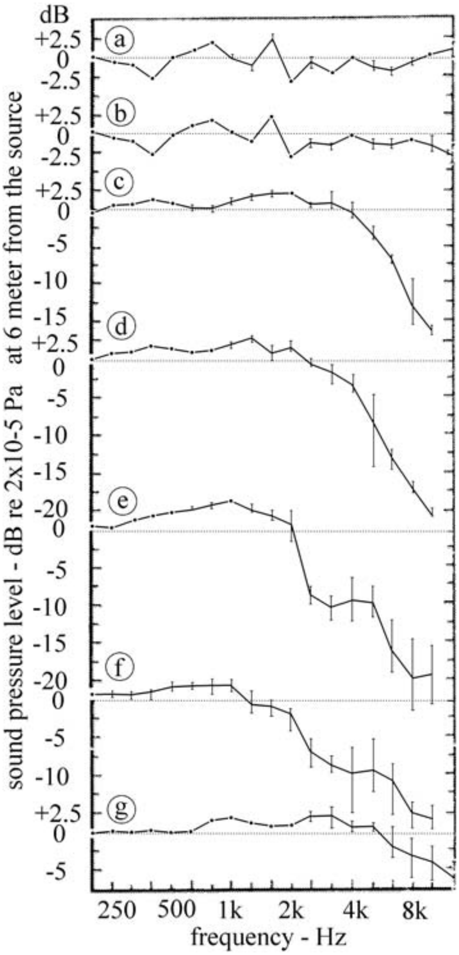


Fig. 4.22. Sound pressure level as a function of frequency for different experimental situations (Martens 1980). Reprinted with permission from the Acoustical Society of America, copyright 2005. **a** Birch trees all sawn down – only earthenware flowerpots with shoots, **b** all birch trees fully defoliated – stems, branches and twigs, **c** 46 birch trees composed of 23 defoliated trees and 23 foliated trees, **d** 46 fully foliated birch trees, **e** 25 fully foliated hazel trees, **f** 26 fully foliated tropical plants of different species, **g** 12 fully foliated privets

Table 4.5. Sound pressure level and attenuation measured in an anechoic chamber with different experimental configurations (Martens 1980). Reprinted with permission from the Acoustical Society of America, copyright 2005

Species	Plants	Total biomass	Total sound pressure level (dB)			Attenuation	Frequency drop	Leaf max. size
	(no.)	(kg)	Flower pots only	Foliated plants	Defoliated	Δ SPL	(kHz)	(mm)
Birch	46	8.4	93.0	92.8		−0.2	2–4	70
Tropical	26	11.5	94.7	92.0		−2.7	1.0–1.25	Various
Hazel	25	3.6	95.0	94.1		−0.9	2.0–2.25	130
Privet	12	2.5	96.0	96.0		+1.2	5.0–6.4	40
Birch	46	5.9	93.0	–	93.8	0.0	8–10	20

show the influence of leaves, stems and twigs, and the excess attenuation is detectable, which increased with frequency.

For the experimental conditions reported by Martens (1980), the canopy acts as an amplifier in the midfrequencies (i.e., for birch 200 Hz to 3.2 kHz, for hazel trees 200 Hz to 2 kHz, for tropical plants 200 Hz to 1 kHz, for privets 650 Hz to 5 kHz).

The influence of the biomass is shown in Table 4.5 and in Fig. 4.23, which underline the relationship between the excess attenuation, biomass, maximum dimensions of leaves and the wave number. The specific capacity of each tree species for noise attenuation seems evident. The response to the noise excitation of tropical plants is very different from that of plants from the temperate zone, as can be observed from the data for curves f, g, e.

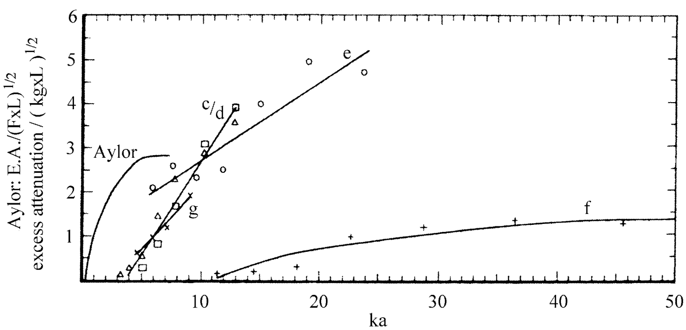


Fig. 4.23. Excess attenuation corrected for biomass, maximum dimension of leaves and length of experimental configuration (4.5 m) as a function of wave number (Martens 1980). Reprinted with permission from the Acoustical Society of America, copyright 2005. *Curve c/d* Birch trees, *e* hazel trees, *f* tropical plants, *g* privets. *Aylor* is based on data given by Aylor (1972b) with leaf area density instead of plant biomass

The efficiency of the filtering action of foliage depends on the noise spectrum and, at the same time, on the sound pressure level of the noise source.

4.3.2.2
Measurements in Reverberation Room

After sound reflection by canopy, branches and leaves, sound refraction takes an important part in the absorption phenomenon. The reverberation room, having a low absorption, is the most appropriate device for detection of the relatively low absorption produced by leaves.

Yamada et al. (1977) proposed a theoretic approach to calculate leaf absorption energy, which depends on several parameters, such as the leaf area, the circular frequency of the leaf, the frequency of the excitation sound, dynamic viscosity and air density.

The absorption coefficient, α_{leaves}, can be calculated with the equation:

$$\alpha_{\text{leaves}} = Gf^2 \tag{4.11}$$

where: f is the frequency, G is a coefficient, depending on the leaf characteristics, (e.g. for a rectangular shape, $G = 0.0002$).

Absorption coefficients and the absorption power of the leaves of trees of different species, versus frequency, were measured in a reverberation room (193 m^3), as can be seen from Fig. 4.24. The influence of an increasing quantity of leaves was expressed by the increasing number of trees in the reverberation room. The absorption coefficient increased with the increasing number of trees in the reverberation room. In this case, the absorption produced by the trees as a whole was measured and it was not possible to differentiate the specific contribution of the leaves. The direct contribution of leaves is shown

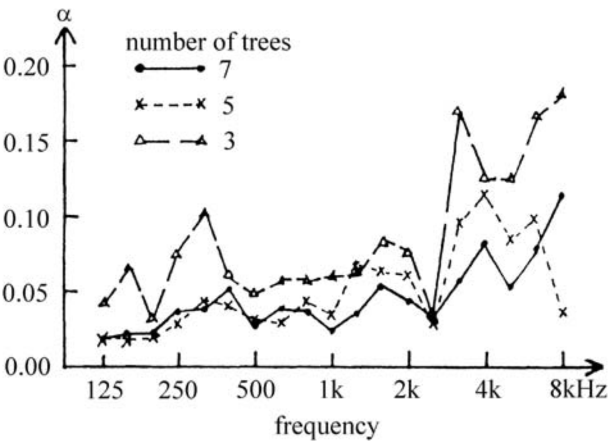


Fig. 4.24. Absorption coefficient versus frequency measured in reverberation room for three, four and five Japanese cypress trees (Yamada et al. 1977)

in Fig. 4.25, in which the absorption power versus frequency is represented for Japanese cypress (trunks with leaves versus trunks only). It can be seen that absorption by trunks only is about one-third of the absorption by trunks

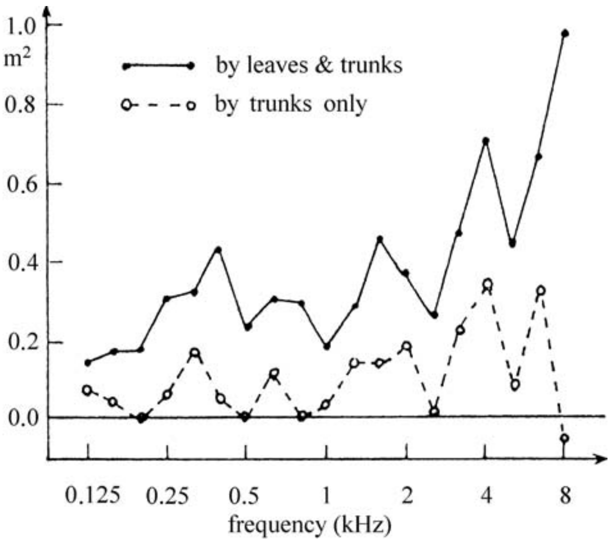


Fig. 4.25. Absorption power versus frequency for Japanese cypress with and without leaves (Yamada et al. 1977)

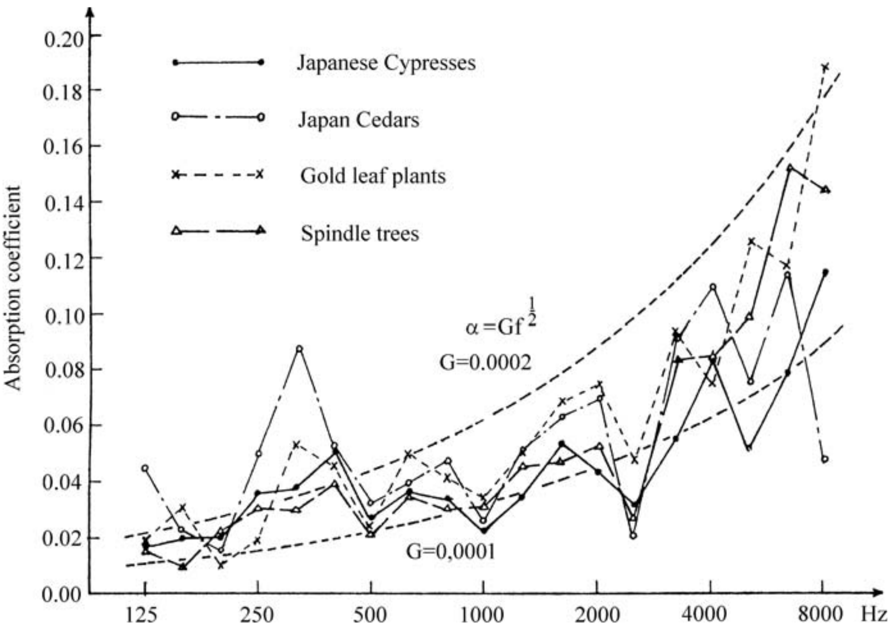


Fig. 4.26. Absorption coefficient versus frequency for different species (Yamada et al. 1977)

with leaves. In this way, it was demonstrated that sound is absorbed by leaves. The same conclusion was deduced from Fig. 4.26, in which the absorption coefficient for different species is represented versus frequency. The proposed hypothesis for the absorption coefficient being proportional to the square root of frequency is valid.

Burns (1979) was interested to understand the mechanism of thermoviscous absorption by white pine (*Pinus strobus*) needles and, for this purpose, measurements in a reverberant room were the best way to answer this question. Fundamental resonances were observed at 4 Hz for 8.8 cm needles and 49 Hz for 2.3 cm needles. Needle-flexing frequency occurred at 20 Hz, particularly at the end of the needle-growing season, when an important amount of identical needles could provide a resonance effect.

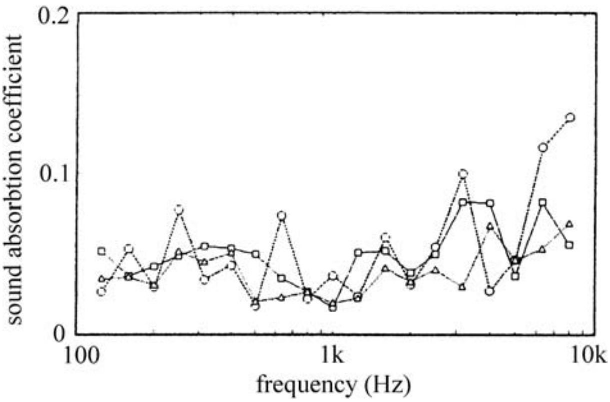


Fig. 4.27. Sound absorption coefficient for sawara cypress with different total leaf surface (Watanabe and Yamada 1996). Reprinted with permission of the Acoustical Society of Japan, copyright 2005. ○ Surface 2.80 m^2, □ surface 4.78 m^2, △ surface 8.70 m^2

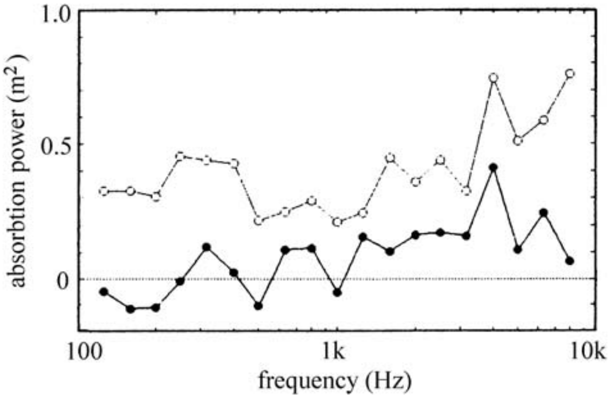


Fig. 4.28. Absorption power versus frequency for sawara cypress with and without leaves (Watanabe and Yamada 1996). ○ With leaves, surface 8.70 m^2, ● without leaves. Reprinted with permission of the Acoustical Society of Japan, copyright 2005

For the measurement of the sound absorption coefficient by foliage, Watanabe and Yamada (1996) introduced several trees (without roots) into a reverberation room and measured the reverberation time with and without trees. One loudspeaker and four microphones were used. The sound source signal was one-third octave band noise, with center frequencies at 125 Hz to 8 kHz.

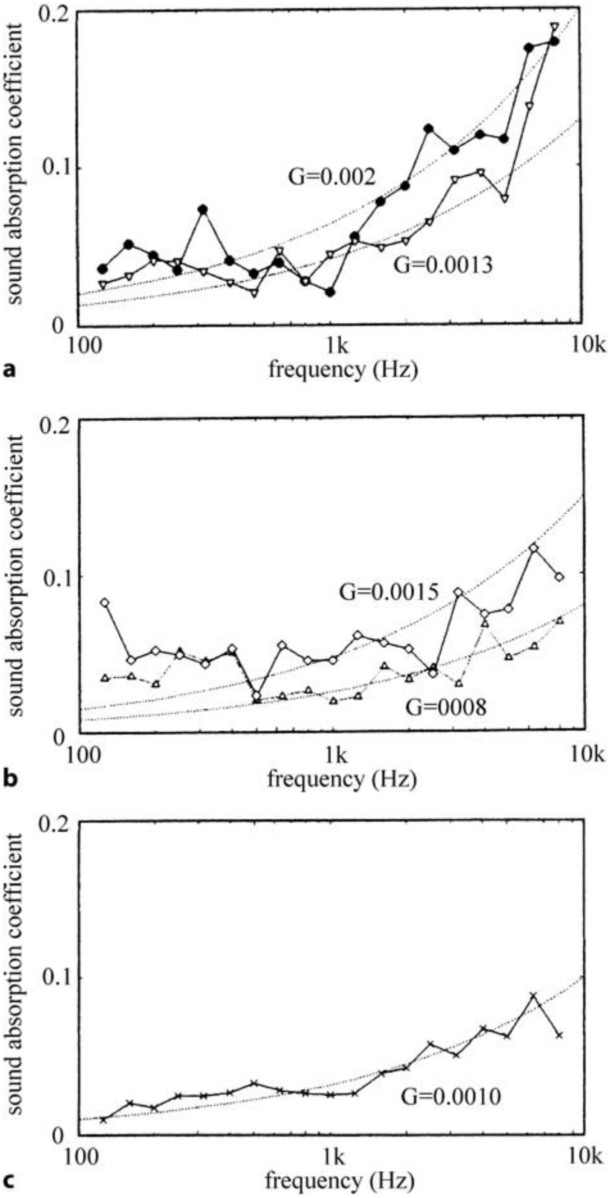


Fig. 4.29. Sound absorption coefficient for trees of different species and different leaves versus frequency (Watanabe and Yamada 1996). Reprinted with permission of the Acoustical Society of Japan, copyright 2005. △ Sawara cypress (*Chamaecyparis pisifera* var. *plumosa*), ● Japanese aucuba (*Aucuba japonica*), ◇ Japanese cedar (*Cryptomeria japonica*), ▽ spindle tree (*Euonymus japonica*)

The absorption coefficient of trees can be calculated as follows:

$$\alpha_m = \frac{55.26xV}{S_m c}\left(\frac{1}{T_m} - \frac{1}{T_0}\right) \tag{4.12}$$

where V is the volume of the reverberation room, S_m is the surface area of the leaves, T_m is the reverberation time with trees and T_0 is the reverberation time of the empty room (without trees).

Figure 4.27 gives the sound absorption coefficient for sawara cypress (*Chamaecyparis pisifera* var *plumosa*) as a function of frequency for three different leaf surfaces, namely 2.80 m^2, 4.78 m^2 and 8.70 m^2. The general trend of curves is very similar. The absorption coefficient is independent of leaf area and frequency.

The calculation of the absorption power – which represents the fraction of the incident acoustic power arriving at the boundary that is not reflected and is therefore regarded as being absorbed by the boundary (Morfey 2001) – and its representation as a function of frequency (Fig. 4.28) has shown that the absorption power of leaves is higher than that of the "skeleton" (composed only of branches). Figure 4.29 represents the variation in sound absorption coefficient versus frequency for different species. The broken lines represent theoretical values determined with the equation $\alpha_{\text{leaves}} = Gf^2$, where G is the frequency absorption factor and f is the frequency. A good agreement is observed between the experimental and theoretical values, for G between 0.0010 and 0.0020.

The attenuation produced by absorption can be calculated with:

$$(Att)_{\text{absorption}} = -10\log\left[1 - \frac{1}{8}GFLf^{\frac{1}{2}}\right] \tag{4.13}$$

where F is the total surface area of leaves per unit volume, $L = 0.3$ m is the diameter of the tree and f is the frequency (i.e. $f = 100$ Hz). Figure 4.30 gives

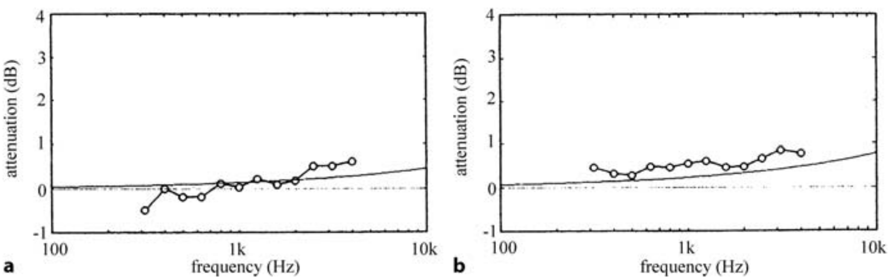


Fig. 4.30. Sound attenuation through absorption by leaves. Theoretical curves and experimental values (Watanabe and Yamada 1996). Reprinted with permission of the Acoustical Society of Japan, copyright 2005. **a** Japanese cedar ($FL = 5.45$, $G = 0.0015$), **b** sudaji ($FL = 6.53$, $G = 0.002$)

theoretical curves and experimental values for sound attenuation through absorption by leaves for two species: coniferous (Japanese cedar, for which $FL = 5.45$ and $G = 0.0015$) and deciduous (Sudajii tree, for which $FL = 6.53$ and $G = 0.002$). In this case, sound attenuation through absorption is less than 1 dB between 300 Hz and 5 kHz.

4.3.2.3 Outdoor Measurements

The mechanism of outdoor sound propagation is summarized in Fig. 4.31. The atmospheric absorption, the ground, the belt of trees, the wind and temperature gradients attenuate the sound which propagates from the source to the receiver along a specific path. Depending on its nature (soft or hard), ground reflections interfere with incident sound, producing attenuation or amplification. The belt of tree acts as a sound barrier. Because of scattering, the canopy of the trees can modify the effectiveness of sound barriers. Wind and temperature vertical gradients refract the sound path (up or down), producing sound shadow zones, contributing or not to the effectiveness of sound barriers (Anderson and Kruze 1992).

In situ full-scale measurements related to the effect of canopy were reported to our knowledge by Lyon et al. (1977), Martens (1981), Piercy and Daigle (1998) and ISO 9613-2 (1996).

Piercy and Daigle (1998) noted that attenuation due to propagation through the canopy increases linearly with the propagation distance, when the radius of a curved ray path is about 5 km. As cited by ISO 9613-2 (1996) when the propagation distance is 10–20 m, the attenuation varies between 1 dB for 250 Hz nominal midfrequency and 3 dB for 8,000 Hz; and, when the propagation dis-

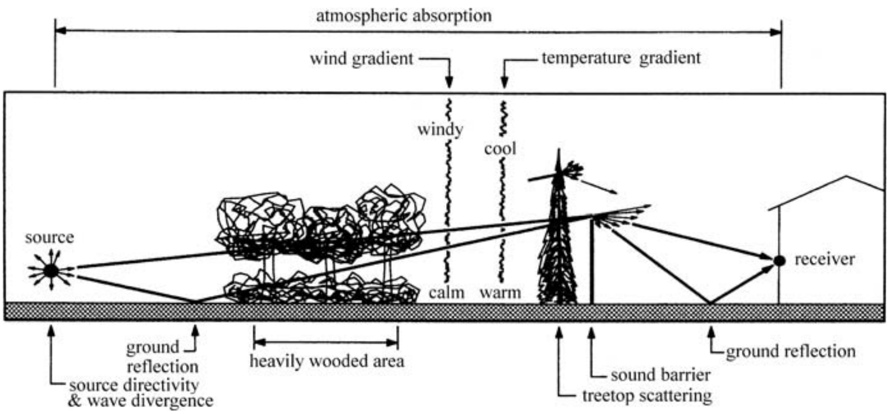


Fig. 4.31. Outdoor sound propagation (Anderson and Kruze 1992)

tance is 20 – 200 m, for the same midfrequencies, the attenuation is respectively 0.04 dB and 0.12 dB.

Excess attenuation as a function of frequency has been studied for sound propagation through and under canopies, for two situations – with and without leaves (Fig. 4.32). The distance between the source and the receiver was 43 m. The frequency spectra with and without leaves diverge above 2.5 kHz. At this frequency, the wavelength is about 12.7 cm and corresponds to the breadth of the leaves. Measurements at various heights in the canopy have shown the leaf effect at 2 kHz.

In situ measurements on foliage attenuation have been reported for tropical forests, temperate forests and for monocotyledonous plants. Eyring's (1946)

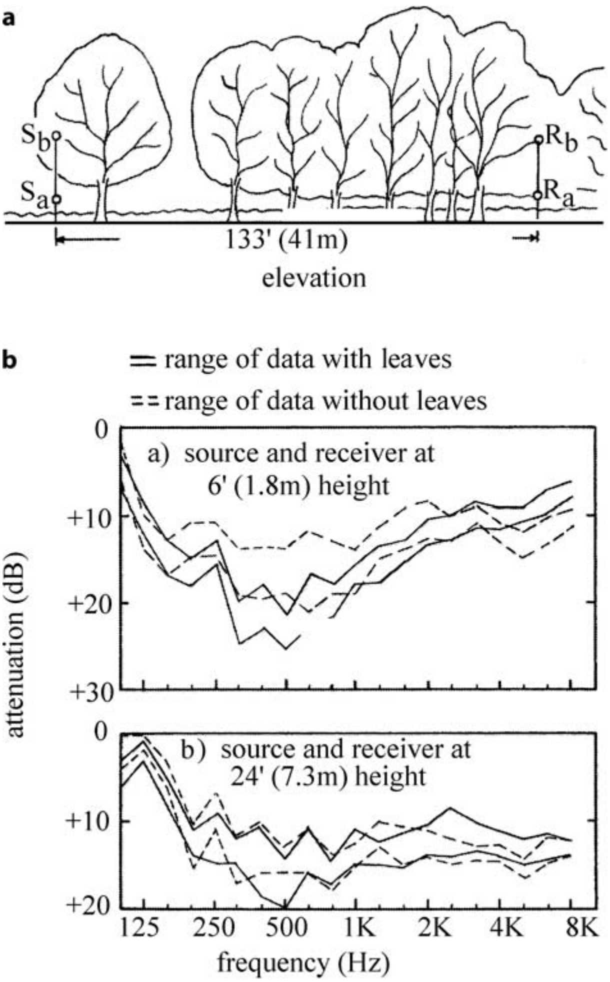


Fig. 4.32. Excess attenuation measured through and under the canopy of maple trees as a function of frequency (Lyon et al. 1977). **a** Under the canopy, **b** through the canopy

pioneering research in tropical rain forests found that foliage has an important role in attenuation, which is correlated with visibility inside the tropical forest. Embelton (1963) noted that, between 200 Hz and 2,000 Hz, vegetation attenuated sound independently of frequency. Branches were identified as resonant absorbers for sound waves between 250 Hz and 1,000 Hz. For deciduous and coniferous trees from temperate zones (cedars, pine, spruce, poplar, elm, maple), no correlation was found between attenuation and visibility. This seems reasonable when comparing tropical and temperate forests. Aylor (1972a, b) studied the influence on the sound field of the canopy of the perennial reed and corn in situ and found an increase in excess attenuation with increasing frequency. Fricke (1984) compared measurements in open ground

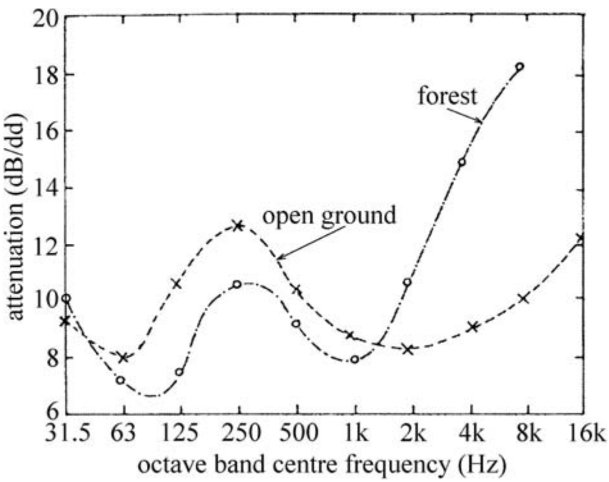


Fig. 4.33. Comparison between attenuation (dB/m) in open ground and in forest (Fricke 1983). Reprinted with permission from Elsevier, copyright 2005

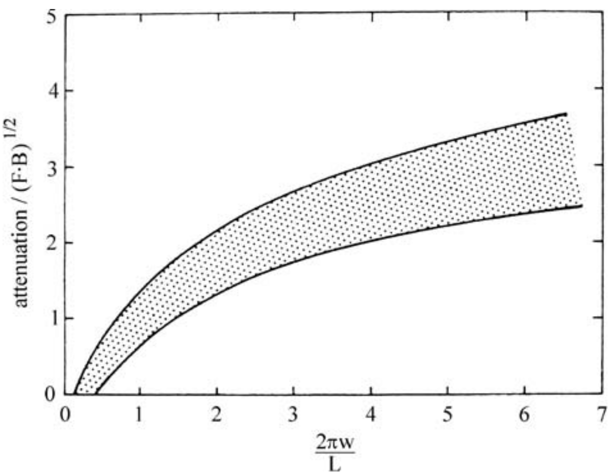


Fig. 4.34. Sound attenuation with leaves (Aylor 1977). Estimation of sound attenuation (dB; *shaded area*) as a function of leaf width corrected with sound wavelength, where F is leaf area per unit volume of canopy, B is breadth of canopy (m) and L is the sound wavelength (m)

and in forest (Fig. 4.33) and noted that scattering by trunks and branches and absorption by foliage and bark are well visible over all frequencies.

Aylor (1977) proposed an empiric approach to quantify noise reduction (expressed as the ratio between attenuation and leaf area per unit volume of canopy and breadth of canopy) and leaf width corrected with the sound wavelength (Fig. 4.34).

To investigate the modes of leaf vibration, Martens and Michelsen (1981) used a laser – Doppler vibrometer system. Laser vibrometry is a suitable technique for measuring vibration velocity in small areas of leaves in a wide range of frequencies (0–100 kHz) without mechanical loading of specimens. The lower limit of the amplitude detection is 1 nm. In a soundfield of 100 dB sound pressure level (*re* 20 µPa), vibration velocities were measured between 10^{-5} m/s and 3×10^{-4} m/s and it was demonstrated that the leaves behave as linear systems. The vibration velocity of leaves are 1–3 orders of magnitude smaller then the vibration velocity of air particles (5×10^{-3} m/s). The leaves behave like plates with different modes of vibration (Fig. 4.35). Only a part

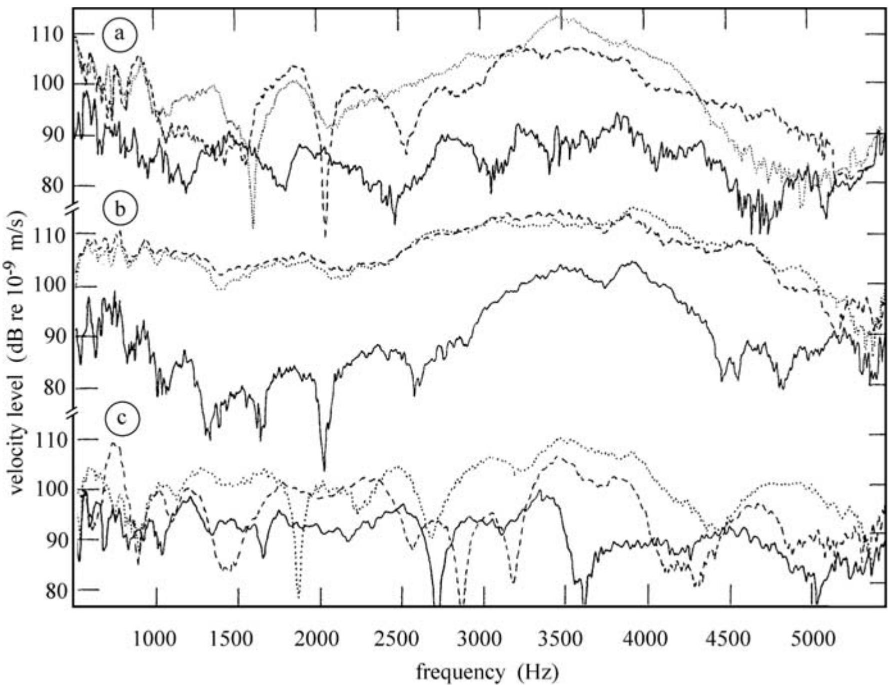


Fig. 4.35. Vibration velocities of a birch leaf (length 60 mm, width 46 mm) measured at different orientations to the sound source (100 dB). SPL: *a* in the center, *b*, *c* near the margin. *Dotted lines* 90°, *broken lines* 45°, *solid lines* 0° (Martens and Michelsen 1981). Reprinted with permission from the Acoustical Society of America, copyright 2005

of the sound energy reaching the leaves will produce vibration energy, the other part will be reflected and diffracted. If the absorption of sound energy is the phenomenon of major importance, the excess attenuation should be linear with the pathlength and foliage density; and this could explain the noise attenuation of plants in the environment.

Aylor (1972a, b) noted that the noise reduction increases with increasing leaf width. Note also that Aylor used in his experiments only monocotyledonous plants, for which the dimensions of the leaves are characterized by a very high length/width ratio. Monocotyledonous (palm with and palm without foliage) behavior was also studied by Bullen and Fricke (1982). The characteristics of the trees studied are the following: the first palm had a trunk diameter of 50 cm and no foliage below 6 m from the ground; the second palm was of about the same size and had very thick foliage extending to the ground and out from the trunk to a radius of 2 m; and the third tree was a big fig. At 1 kHz, the results for palms were similar and the cross-scattering area was 0.4 m. Measurements on a big fig, having a diameter of 1 m and a big canopy with leaves and both large and small branches spreading at 30 m, showed that the normalized cross-scattering area was 2 m. In this case, the scattering produced by the trunk and canopy (branches and foliage) was significant (Fig. 4.36).

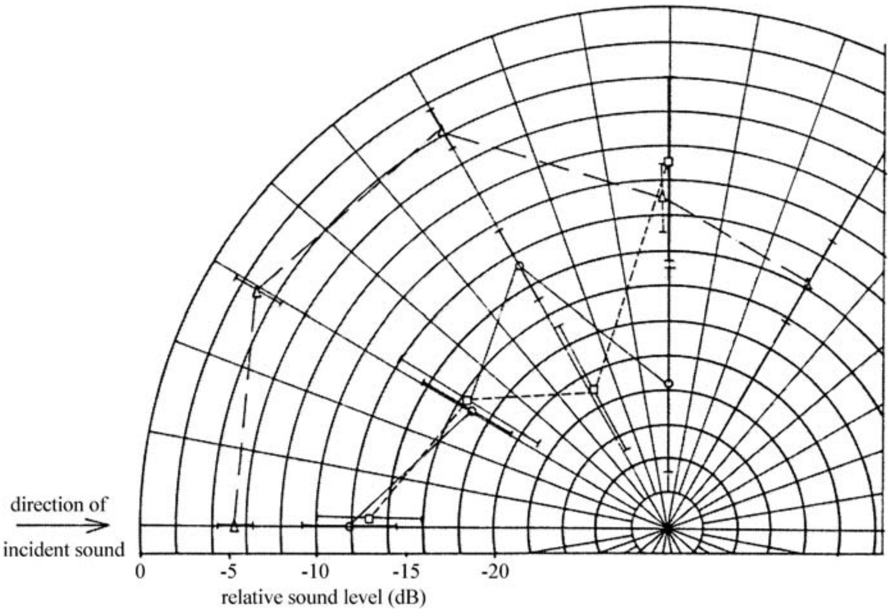


Fig. 4.36. Relative sound level (dB) of sound scattered by trees (Bullen and Fricke 1982). Reprinted with permission from Elsevier, copyright 2005. *Circles* Palm without important foliage, *squares* palm with foliage, *triangles* fig. The direction of the incident sound was between 0° and 90°

The normalized scattering cross-section (σ_s) was measured by emitting a pulse of $\Delta t = 1$ ms duration from the source and recording the level of the reflected pulse. The scattering length is $L_s = 1/(N \times \sigma_s)$, where N is the number of trees/m^2. The absorption length is $L_a = 1/(N \times \sigma_a)$. If the absorption is not a dominant process, we have: $L_a \ll L_s$.

Bullen and Fricke (1982) stated that, at 500 Hz, for a conventional, typical tree of 5 m height and 50 cm diameter, with average foliage having a normalized absorption cross-section of 5 cm, at 2 kHz, the absorption cross-section can be between 10 cm and 15 cm. The variation in the reduced absorption cross-section as a function of frequency for trees with different shape and size of canopy and foliage was shown previously in Fig. 4.17. A peak of absorption cross-section was observed at 2 kHz for all species. The maximum was for magnolia (having large leaves) and the minimum for ash (having relatively small leaves). The wavelengths of these frequencies are compatible with the leaf sizes, since the maximum dimension of the leaves is between 0.5 λ and 1.0 λ. Resonances of branches were identified by Embelton (1963)

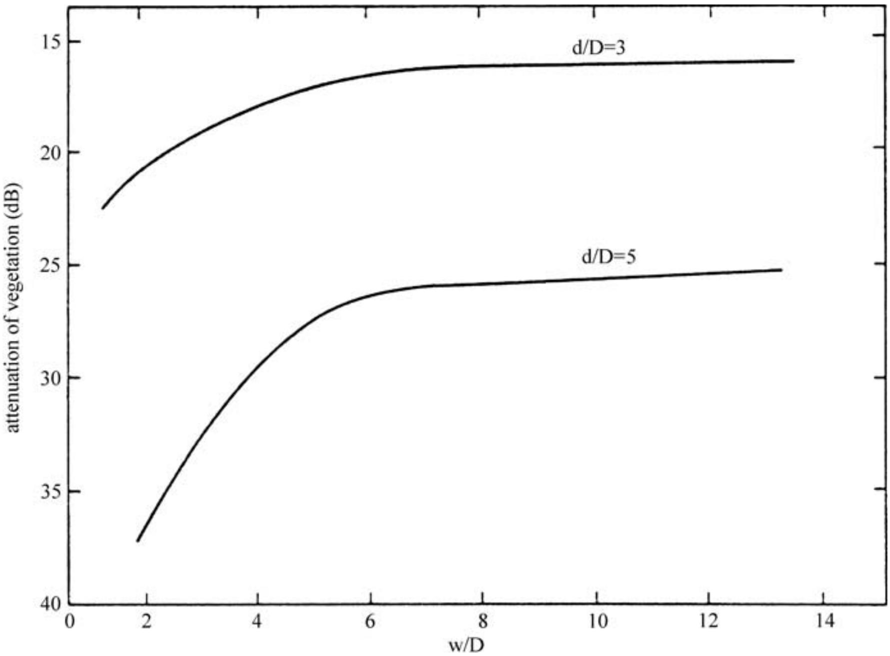


Fig. 4.37. Effect of the width of a belt of trees on excess attenuation (Bullen and Fricke 1982). Reprinted with permission from Elsevier, copyright 2005. w Width of the belt of infinite length. The mean path length before absorption is $L_A = 1/N\sigma_A$; the free path length is $L_s = 1/N\sigma_s$. $D^2 = 0.5\,L_A L_s$. d Depth on an infinitely wide belt of trees, N number of trees/m^2

between 275 Hz and 400 Hz, corresponding to a branch length between 1.2 m and 1.8 m.

The effect of foliage integrated into the width of a belt of vegetation is shown in Fig. 4.37. If the ratio $w/D > 5$, the attenuation is constant (about 26 dB for the ratio $d/D = 5$; and about 16 dB for the ratio $d/D = 3$). For the general case, it was stated that about 3 dB excess attenuation may be gained by making the belt approximately as wide as its depth.

The effect of foliage on excess attenuation can be well observed when comparing experiments in winter and summer (Price et al. 1988). In the absence of leaves, attenuation was considerably low. A peak of attenuation was found at 200 Hz and was attributed to the ground. For frequencies higher then 1,000 Hz, the attenuation gradually increased and was attributed to the trunks and foliage.

The influence of solitary tree foliage density on noise reduction was studied by Schaudinischky et al. (1982). The trees were instrumented as shown in Fig. 4.38a. Measurements "in situ" in a forest stand were performed at different distances from the source, following the scheme presented in Fig. 4.38b. A quality score (Q_{res}) ranging from 10 to 100 was proposed to determine the acoustic

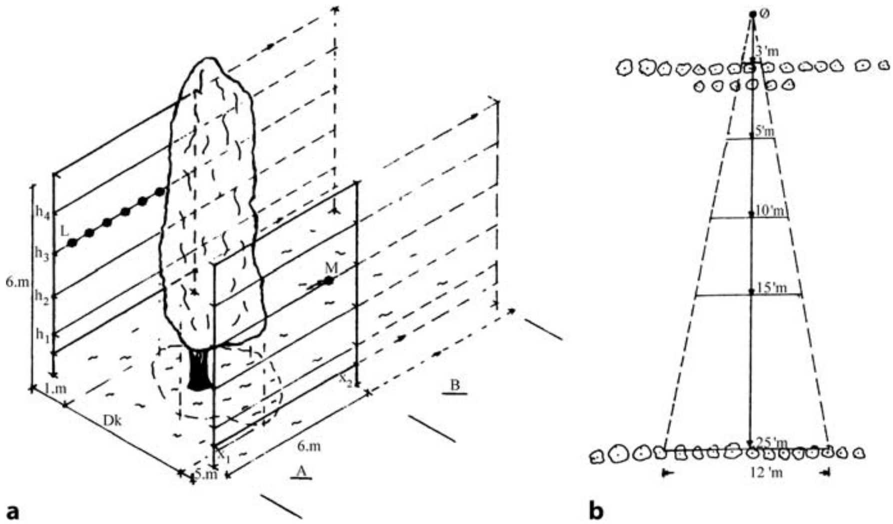


Fig. 4.38. Experimental set up for noise reduction measurement of a solitary tree (Schaudinischky et al. 1982). **a** Measurements on a solitary tree. *A* Measurement zone for tree, *B* measurement for free field, *L* noise source – loudspeaker position at different heights (maximum 6 m), *M* motorized mobile microphone, D_k diameter of the canopy, n_1–n_4 measurement points in *vertical direction*, x_1–x_n measurement points in *horizontal directions*. **b** Measurements on forest stands. Only the first two rows of trees are epresented, as well as the last row. The measurements were taken at 3 m, 5 m, 10 m, 15 m and 25 m from the source

quality of each tree, taking into account the foliage density, the growth rate and the noise reduction effectiveness. The measured parameter was the difference in sound pressure level, Δ_L, behind and below the tree, in a frequency range between 63 Hz and 8,000 Hz in one-third octave band analysis.

The sound pressure level as a function of canopy diameter ($\Delta\overline{L}$) was expressed in dB/m and was deduced from the empirical equation:

$$\Delta\overline{L} = \Delta_L/D_k(\mathrm{dB/m}) \tag{4.14}$$

The quality score was calculated with 4.15:

$$Q_{\mathrm{res}} = \left[60 \log \Delta\overline{L} + 10 \times \mathrm{e}^{0.23} \frac{t_D}{t_{D_{\mathrm{ref}}}}\right] - B \tag{4.15}$$

where t_D is the growing time (years) to reach 4 m height, $T_{D_{\mathrm{ref}}}$ is the growing time (years) to reach 12 years of age and B is the correction coefficient related to species (0 for coniferous and 5 for deciduous species). Δ_L is the difference in sound level.

The quality score factor for different species is given in Table 4.6. Broadleaves trees score better than pine, whereas cypress, thuya and callitris occupy an intermediate position.

The influence of species on noise reduction as a function of frequency is shown in Fig. 4.39. It is evident that deciduous species (having an important volume of canopy and leaves) are more effective in noise reduction than coniferous species. The influence of the density of leaves and branches (expressed by measurements at different heights in the canopy as a function of frequency) is

Table 4.6. Characteristics of solitary trees (Schaudinischky et al. 1982)

No.	Species	Canopy diameter (D_k; m)	t_D (years)	SPL related to canopy diameter $\Delta\overline{L} = \Delta_L/D_k$ (dB/m)	Quality score factor (Q_{res})
1	*Callitreis verrucosa*	7	8	0.63	55
2	*Thuya orientalis*	5	8	0.74	48
3	*Cupressus sempervirens* var. *Hor.*	6	6	0.78	48
4	*C. sempervirens* var. *pyr.*	4	6	0.58	45
5	*Pinus halepensis*	7	6	0.39	42
6	*P. pinea*	7	10	0.50	46
7	*Acacia cyanophylla*	9	5	0.54	59
8	*Eucalyptus camadulensis*	7	4	0.57	56
9	*Ficus retusa*	9	10	0.69	61
10	*Quercus calliprinos*	7	12	0.53	47
11	*Q. ithaburensis*	5.5	12	0.40	32
12	*Ceratonia siliqua*	7	12	0.54	55

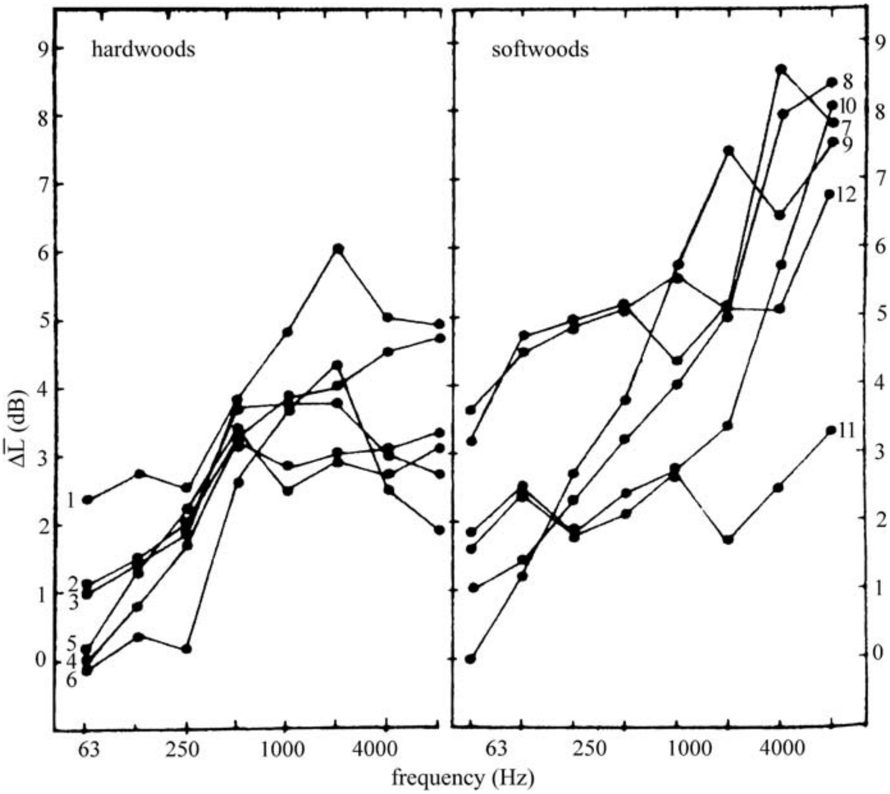


Fig. 4.39. Noise reduction related to canopy diameter, D_k, as a function of frequency and expressed by $\Delta\overline{L} = \Delta_L/D_k$ (dB/m; Schaudinischky et al. 1982). The *numbers* correspond to different species: *1 Eucalyptus camaldulensis*, *2 E. camaldulensis*, *3 E. camaldulensis*, *4 Ceratonia siliqua*, *5 C. siliqua* and *Quercus calliprinos*, *6 C. siliqua* and *Q. calliprinos*, *7 Q. calliprinos*, *8 Q. ithaburensis*, *9 Collitris verrucosa*, *10 Cupressus sempervirens* var. *pyr.*, *11 C. sempervirens* var. *Hor.*, *12 Pinus pinea* and understand, *13 P. pinea*, *14 P. halepensis*, *15 P. halepensis*

shown in Fig. 4.40. The dispersion of measurements in the canopy of *Cupressus* is less important than in *Ceratonia*. The effect of species canopy on attenuation is shown in Fig. 4.41. The dispersion of experimental values is very high and it is difficult to extract a precise law. However, it can be noted that attenuation increases with frequency.

Noise reduction by forest stands composed of the same species was examined (Table 4.7). It was found that broadleaved trees reduce noise better than conifers. Noise abatement is stronger when the foliage extends close to the ground, as in young stands or in the presence of undergrowth. Noise reduction within the stand as a function of the distance from source is shown in Fig. 4.42 for two values of sound pressure level, namely < 0.20 dB and > 0.20 dB. As

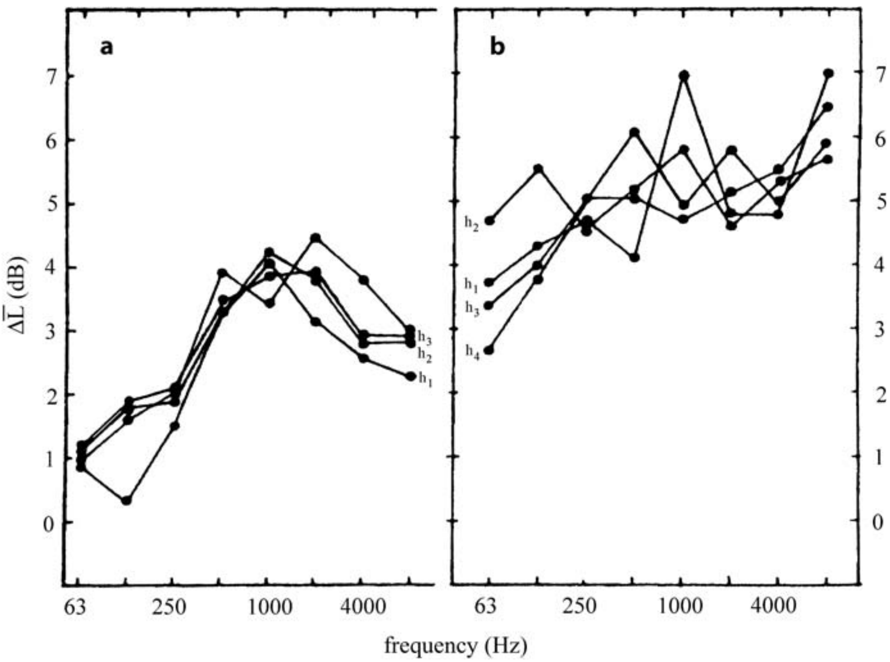


Fig. 4.40. Noise reduction expressed by $\Delta\overline{L}$ produced by solitary trees, as a function of the height in the canopy and frequency (Schaudinischky et al. 1982). **a** *Cupressus*, **b** *Ceratona*

expected, in both cases, the increase in distance from the source has a positive influence on the noise reduction produced by the stand. To achieve a good noise reduction, it was suggested to plant rows which would be felled alternately to maintain dense foliage near the ground. Suitable species with dense foliage are pyramidal *Cypressa*, *Callitris*, *Thuya*, *Ceratonia*, *Eucalyptus*, *Quercus*.

It may be important to distinguish between the effect of a solitary tree, a group of trees and a stand forest (Fricke 1984). The acoustical response of a group of trees is associated with the ground effect. The impedance of the ground over which the sound propagates affects the attenuation rate, mainly in the 250, 500 Hz frequency range. Scattering by the boles and branches and absorption by the bark and foliage are higher-frequency phenomena. These results are similar to those obtained by Kragh (1981). It appears that scattering, rather than absorption as suggested by Aylor (1972a, b), is the more important phenomenon at the midfrequencies. At high frequencies, absorption takes over as the dominant phenomenon. “If scattering is the cause of attenuation through vegetation then more energy is back-scattered and so the decay with time becomes less as the decay with distance increases” (Fricke 1984).

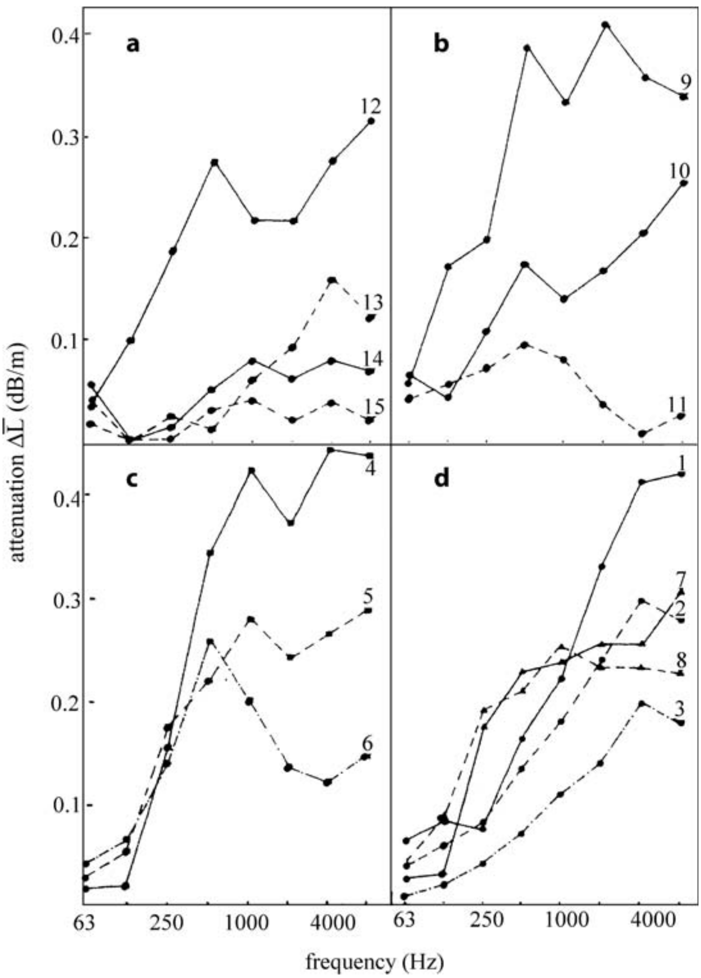


Fig. 4.41. Analysis of noise reduction expressed by $\Delta\overline{L}$ produced by coniferous and deciduous species (Schaudinischky et al. 1982). **a** *Pinus* – measurements on four trees, **b** *Cupressus sempervirens* – measurements on three trees, **c** *Ceratonia siliqua* – measurements on three trees, **d** *Eucalyptus camaldulensis* – measurements on five trees. The *numbers* correspond to different species, as noted in Fig. 4.39

A considerable amount of data (15 stands, Table 4.8) on the "in situ" attenuation rate of forests was published by Tanaka et al. (1979). The profile of stands was complex, composed of coniferous (Japanese black pine, Japanese cedar, Japanese red pine) and deciduous species (mainly beech), as can be seen from Fig. 4.43a. The regression analysis between noise attenuation and distance was established using linear or exponential models ($Y = ab^{\log x}$, where Y is attenuation, x is distance, a and b are experimental coefficients). With the space

Table 4.7. Characteristics of forest stands of different species (Schaudinischky et al. 1982)

No.	Species	Tree density (no./ha)	Average height (m)	Diameter at 1.30m (cm)	Degree (%)	Canopy (m)	SPL related to canopy diameter $\Delta\overline{L}$ [(A)/m; dB]
1	*Eucalyptus camadulensis*	6,000	2.5	1	80	0.20	0.28
2	*E. camadulensis*	3,000	6.0	7	80	0.50	0.18
3	*E. camadulensis*	1,000	14.0	15	50	2.0	0.11
4	*Ceratonia siliqua*	620	5.0	20	80	0.50	0.32
5	*C. siliqua* and *Quercus calliprinos*	700	3.5	10	80	0.20	0.22
6	*C. siliqua* and *Q. calliprinos*	400	3.5	10	40	1.0	0.14
7	*Q. calliprinos*	2,500	3.0	8	90	0.20	0.25
8	*Q. ithaburensis*	2,500	4.0	6	80	0.20	0.24
9	*Callitris verrucosa*	1,000	8.0	15	70	1.0	0.30
10	*C. sempervirens* var. *pyr.*	800	14.0	18	40	0.50	0.16
11	*C. sempervirens* var. *Hor.*	800	14.0	18	60	0.50	0.06
12	*Pinus pinea* – understand	1,500	12.0	15	80	0.20	0.24
13	*P. pinea*	600	12.0	20	70	2.50	0.08
14	*P. halepensis*	1,200	12.0	13	80	2.0	0.06
15	*P. halepensis*	350	18.0	31	50	10.0	0.02

available in this book it has been decided to select only four stands, for which the regressions are shown in Fig. 4.43b, c.

From previous data, it seems that the factors which have a positive influence on the efficiency of forest stands for noise attenuation are: higher stand density, mixed species of trees, larger quantity of leaves (Table 4.9). Measurements in summer and in winter for deciduous stands clearly show the effect of leaves on attenuation.

Here is the place to mention the remarkable pioneering activity (Martens 1981) in the Department of Botany at the University of Nijmegen (The Netherlands) in the field of noise abatement with vegetation and landscape planning. As an example in what follows, the relationships between noise attenuation and four types of forest vegetation (stands, belts, etc.) are described in Tables 4.10, 4.11, 4.12. The acoustic climate was expressed by the variation in excess attenuation versus the frequency in planted forests during 1959–1961, located in Flevopolder and composed of the following species: beech (*Fagus sylvaica*), ash (*Fraxinus excelsior*), spruce (*Picea abies*), poplar with mixed

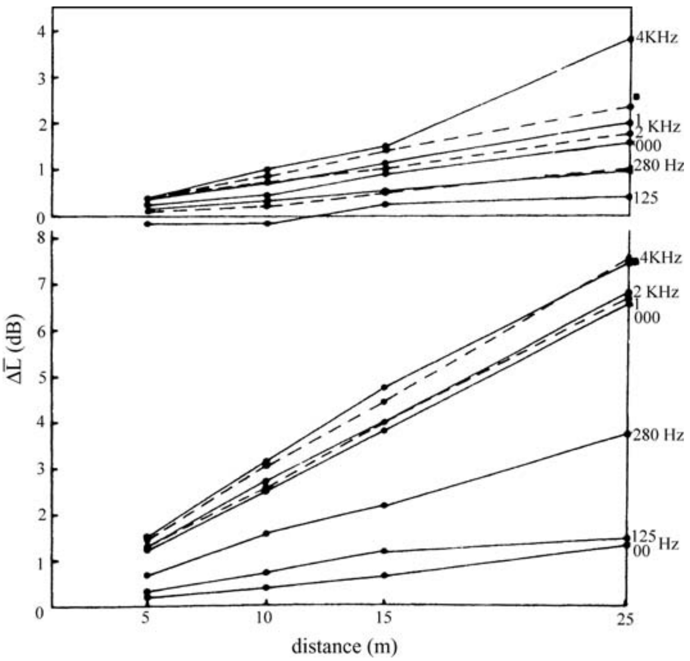


Fig. 4.42. Noise reduction (expressed by $\Delta\overline{L}$) as a function of the distance in the stand, for two levels of excitation (Schaudinischky et al. 1982). The *upper graph* is for L_5 <0.20 dB(A); and the *lower graph* is for L_{50} > 0.20 dB(A)

deciduous species (*Populus x canadensis*, *Quercus robur*, *Carpinus betulus*, *Corylus avellana*, *Alnus glutinosa*, *Acer campestre*), or in a belt of spruce (*Picea sitchensis*) and various deciduous trees in the Botanical Garden of the Nijmegen University – the *Stellario carpinetum* (Fig. 4.44). A flat grassfield covered with short grasses of 50 mm maximum height was taken as a reference for the acoustical measurements. The measurements were performed with white noise. The sound pressure level of unfiltered noise was 104 dB and 20 µPa at 6 m in the front of the woofer during all experiments. The microphones were placed at 1.2 m and 3.9 m from the soil; and the distances between the source and the receiver were 6, 12, 24, 48 and 96 m. The frequency spectrum was measured at each distance and analysed in one-third octave bands with center frequencies between 50 Hz and 10 kHz.

From Fig. 4.44a–d, one observes the effect of frequency on excess attenuation for all experiments. A first maximum frequency (noted f') in the low frequency domain (< 250 Hz) can be seen, related probably with the experimental arrangement and is produced by the destructive phase difference between the direct and ground-reflected sound waves (angle φ). For some experiments related to forest stands, f' is between 160 Hz and 250 Hz, while for the grass

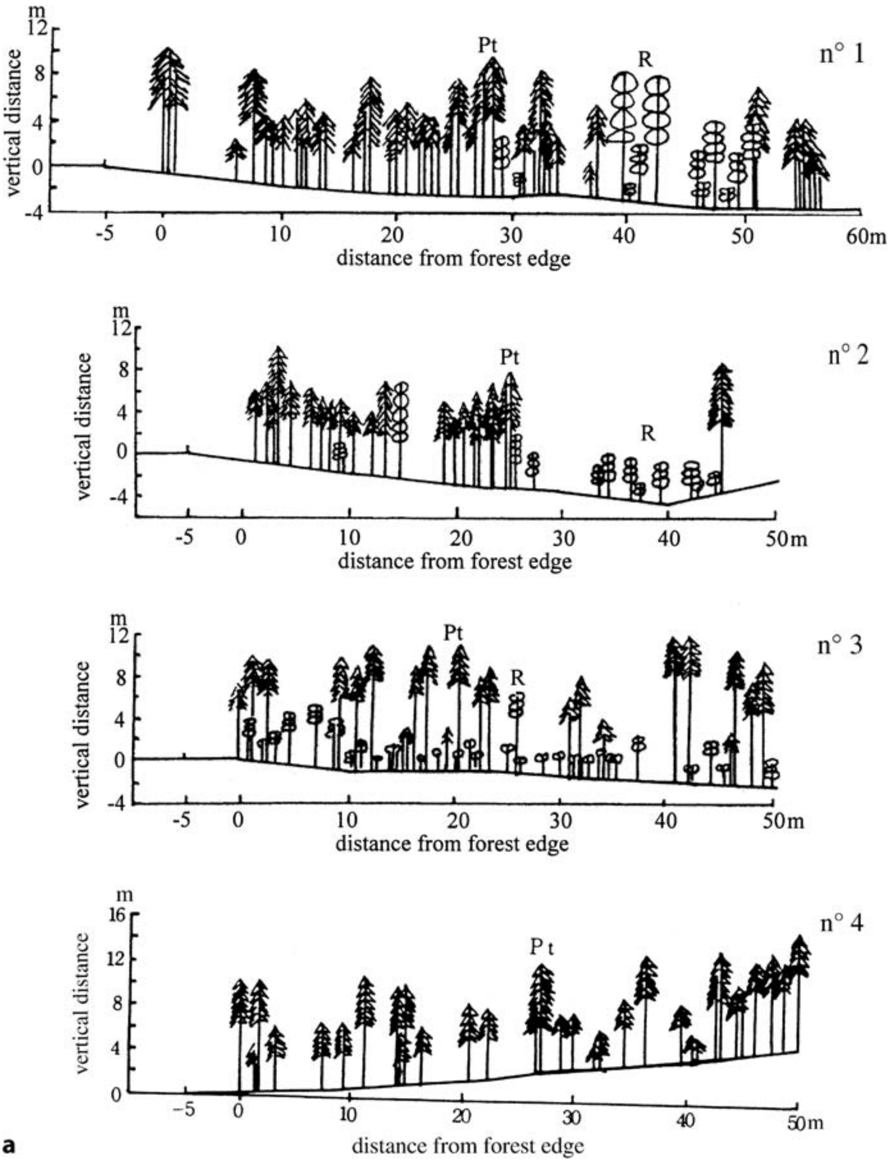
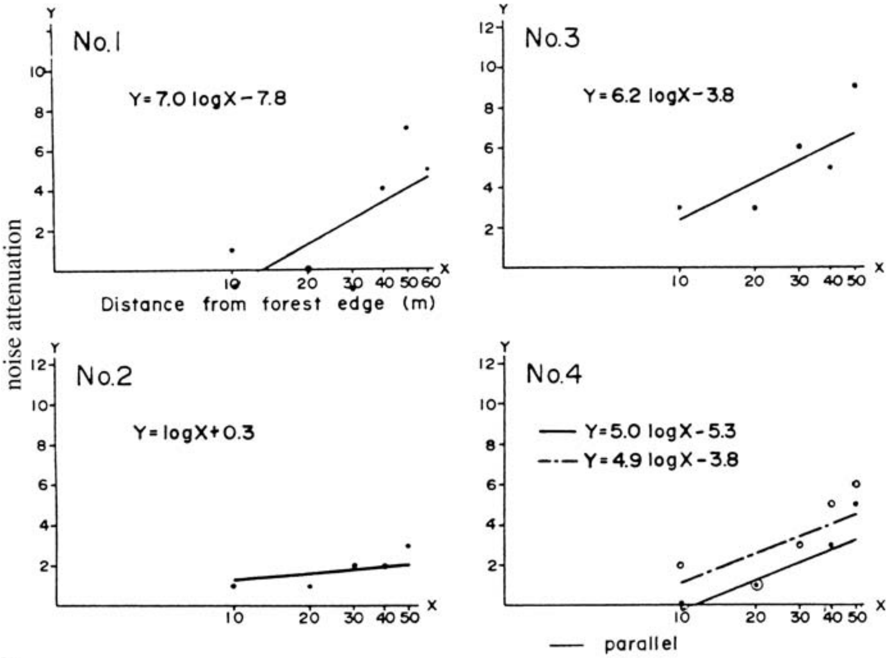


Fig. 4.43. Stands for noise attenuation measurements (Tanaka et al. 1979). **a** Profile of stands. *Stand 1* Dominant species – *Pinus thunbergii* (*Pt*), mixed with *Robinia* spp (*R*), density 2,900 trees/ha, 7.2 m height. *Stand 2* The same species as stand 1, density 2,500 trees/ha, 7.8 m height. *Stand 3* The same species, density 1,900 trees/ha, height 9.1 m. *Stand 4 P. thunbergii*, density 3,500 trees/ha, 6.7 m height. **b** Linear regression relationships between noise attenuation [−dB(A)] and distance (m), for the stands represented previously. **c** Logarithmic regression relationships between noise attenuation and distance, for the same stands



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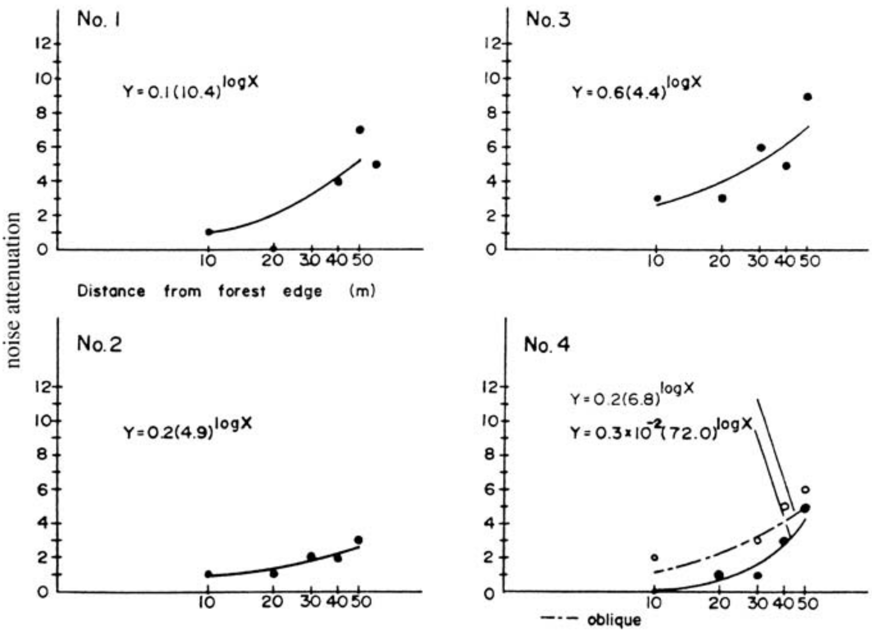

c

Fig. 4.43. (continued)

Table 4.8. Dendrologic characteristics of stands and corresponding attenuation as a function of distance into the stand (Tanaka et al. 1979)

Stand no.	Dominant level				Dominate level						
	Dominant species	Density	Height	Basal area	Density	Relative attenuation (dB) as a function of distance					
		(No./ha)	(m)	(m^2/ha)		10 m	20 m	30 m	40 m	50 m	60 m
1	Pine – mix	2,900	7.2	16.1	Thin	1	0	−1	4	7	5
2	Pine – mix	2,550	7.8	15.9	Thin	1	1	2	3	3	
3	Pine – mix	1,900	9.1	26.0	Thin	3	3	6	5	9	
4	Pine – pure	3,500	6.7	23.8	Thin	2	1	3	5	6	
5	Pine – mix	3,000	13.7	44.2	Thin	0	0	1	1	5	
6	Sugi – pure	4,750	6.0	31.1	Thin	1	2	4	6	8	
7	Sugi	3,400	2.6	21.7	Dense	1	3	3	5	6	
	Hinoki	1,288	–	–		1	4	6	7	9	
8	Sugi – pure	3,920	4.0	45.1	Medium	2	4	5	6	9	10
9	Sugi – pure	4,670	7.3	39.7	Medium	2	4	7			
10	Sugi – pure	4,800	7.7	38.3	Medium	3	4	7	7		
11	*Alnus*	3,000	10.9	35.6	Dense	1	3	6	8	9	
	Robinia	300	4.0	0.4		0	1	5	6	7	
12	*Alnus*	2,600	9.1	26.1	Dense	4	3	7	9	10	
	Robinia	1,400	3.3	1.6		0	1	3	4	6	
13	*Fagus*, *Lindera*	1,800	7.5	42.8	Dense	3	1	5	5	7	
	Clethera	4,300	1.0	1.5		3	4	7	8	8	
14	*Fagus*, *Quercus*	1,500	11.0	49.0	Dense	2	4	3	4	6	
	Acer	300	2.5	0.7		1	4	4	6	8	
15	*Fagus*, *Quercus*	2,500	10.5	67.2	Dense	3	2	5	5	8	
	Clethera	500	1.5	0.5		2	3	5	6	7	

Table 4.9. Best fit reverberation parameters and corresponding prediction of attenuation (Huisman and Attenborough 1991). Reprinted with permission by the Acoustical Society of America, copyright 2005

Parameter	Frequency (Hz)				
One-third octave band center frequency	500	630	1,000	2,000	4,000
Absorption (dB/s)	0	0	0	3	10
Best fit parameters:					
(a) Diameter *De* (m)	0.01	0.02	0.04	0.08	0.16
(b) Reflection factor *Re*	0.1	0.1	0.1	0.1	0.1
Scattering attenuation at 100 m:					
(a) Total scattering attenuation (dB)	−0.8	−1.6	−3.1	−6.3	−12.8
(b) Direct field attenuation (dB)	−0.8	−1.7	−3.3	−6.6	−13.2

Table 4.10. Some characteristics of forests and stands experimented by Martens (1981)

Species	Parameters of trees (m)		Distance (m) between:		Ground	Canopy
	Diameter	Height	Rows	Trees		
Beech forest	11	7.5	2.5	1.35	50 mm litter	Closed
Ash forest	4	6.0	1.4	1.1	Herbs, mosses	Open
Spruce, fir forest	11.5	8	2	1.8	50 cm layer	Closed
Spruce belt	10	7.5	–	–	30 cm grass, reeds	Closed
Mixed poplar forest	29	12	3.3	7.7	Dry wood, mosses	Open
Mixed deciduous species – *Stellario carpinetum*	Various	17	–	–	20–60 mm litter	Open

field it is close to 1,000 Hz. For the spruce belt, f' is between 500 Hz and 800 Hz. These differences could be explained by the different composition of soil surfaces (dry matter, water content, porosity). Forest soil is softer than the soil of the grass field. The second excess attenuation maximum between 2,000 Hz and 4,000 Hz, which is present in all forest types and absent in the grass field, can be attributed to leaves. In the midfrequency range, between 1 kHz and 2 kHz, the excess attenuation is relatively low and quite constant, in deciduous forest stands. This zone, around 2 kHz, was referred to as the "sound window" in the acoustic climate of the plant community and was considered important for the acoustic communications of birds and animals living in the forest. In the high frequency range, a second, but less important maximum can be observed for the measurements in forest only (not in the grass field). It was suggested that this second maximum could be attributed to propagation phenomena in a waveguide (tree branches).

The recapitulation of the experimental data presented by Martens (1981) allows to note that, in most of the one-third octave band studied, in beech and ash forest stands the excess attenuation was at least 10 dB per 100 m with the receiver and source at the same height (1.2 m) and was at least 5 dB per 100 m with the receiver at a height of 3.9 m. Compared with beech and ash stands, in mixed deciduous stands, a *sound window* was detected around 2 kHz, and the ground effect was extended more towards the high frequency range, compared with beech and ash stands. In coniferous spruce stands, the highest excess attenuation was measured, such as 10 dB per 100 m with the receiver at 1.2 m height and 7 dB per 100 m with the receiver at 3.9 m. In the spruce belt, the attenuation, for the same conditions as for the spruce stand, was respectively 7 dB per 100 m and 4 dB per 100 m. As expected, the highest attenuation was found in closed forest stands and not in tree belts.

Martens (1981) concluded that trees, a belt of trees at least 12 m wide and forest stands can be efficiently used to abate noise pollution in urban areas.

Table 4.11. Centre-frequency of one-third octave bands at which appears the first sound pressure minimum (Martens 1981). Reprinted with permission from Elsevier, copyright 2005

Parameter	Distance (h) between source (s) and microphone (r); and path length (Δr) difference between direct and soil surface-reflected sound waves								
	$h_s = h_r = 1.2$ m						$h_s = 1.2$ m; $h_r = 3.9$ m		
	Distance	6 m	12 m	24 m	48 m	96 m	24 m	48 m	96 m
	Δr (m)	0.46	0.24	0.12	0.06	0.03	0.39	0.19	0.10
	Grassfield								
Frequency	Hz	315	500–640	500–800	640–800	500–1,000	400	500	500
Phase	Angle	27	17–53	76–115	130–140	155–166	15	79	126
	Spruce fir belt								
Frequency	Hz	315	250–315	315	315	200–250	250	250	250
Phase	Angle	27	97–115	140	158	173	76	130	155
	Beech forest								
Frequency	Hz	160	250	250	200–250	200–250	200	200	200
Phase	Angle	58	115	148	166	173	97	137	158
	Spruce fir forest								
Frequency	Hz	200	200–250	200	200	200	200	200	200
Phase	Phase	58	115–130	155	166	173	97	137	158
	Stellario carpinetum								
Frequency	Hz	250	250	250	250	–	250	250	–
Phase	Angle	58	115	148	166	–	76	130	–
	Mixed poplar forest								
Frequency	Hz	250	250	250	250–315	250	250	250	250
Phase	Angle	58	115	148	158–166	173	76	130	155
	Ash tree								
Frequency	200	250	250	250	250	200–250	–	200	250
Phase	83	115	148	166	173	137	–	137	155

NB: The phase-reflecting angle in degrees is calculated as $\varphi = \left(\frac{1}{2} - f' \frac{\Delta r}{c}\right) \times 360$, where c is the sound velocity in air and f' is the frequency at which the first maximum occurs.

Table 4.12. Excess attenuation as a function of center-frequency analyzed in one-third octave bands (Martens 1981)

Vegetation	Excess attenuation (dB/100 m, at frequencies ranging over 1 – 10 kHz)										
	1 Hz	1.25 Hz	1.6 Hz	2.0 Hz	2.5 Hz	3.2 Hz	4.0 Hz	5.0 Hz	6.4 Hz	8.0 Hz	10 Hz
Beech tree	12.7	10.4	10.1	7.9	9.7	8.9	11.3	13.3	15.0	16.7	18.5
Ash tree	9.0	8.9	11.7	8.6	13.7	15.6	16.6	18.4	21.7	24.8	28.5
Poplar forest	8.9	8.0	9.4	6.9	8.3	9.1	13.4	16.3	20.5	21.6	24.0
Spruce forest	9.6	8.5	13.5	15.3	19.0	21.5	24.7	28.1	33.2	37.4	35.0
Spruce belt	7.2	7.1	11.0	8.9	11.8	13.7	19.2	21.4	21.3	27.2	29.8

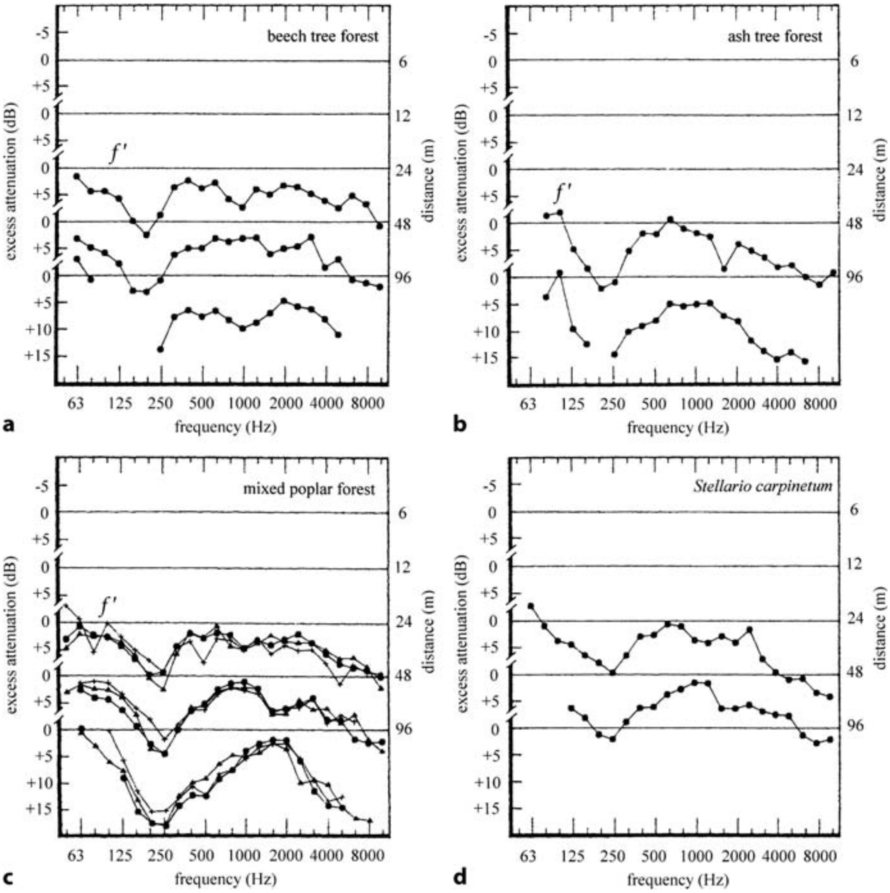

Fig. 4.44. Excess attenuation versus frequency for different distances between source and receiver (Martens 1981). Reprinted with permission from Elsevier, copyright 2005. **a** Beech forest, **b** ash forest, **c** mixed poplar forest, **d** *Stellario carpinetum*, **e** spruce forest, **f** spruce belt, **g** grassfield

4.3.3 Reverberation in a Forest Stand

The well audible reverberation in a forest demonstrates interference between the direct and ground-reflected sound and the scattering effects induced by trees and branches, the ground and possible air turbulence and diurnal variations in meteorological conditions.

It was supposed that the reverberant field consists of randomly reflected particles for which the source location is not relevant. Transient acoustic signals are distorted by the reverberation which is produced by the superimposition

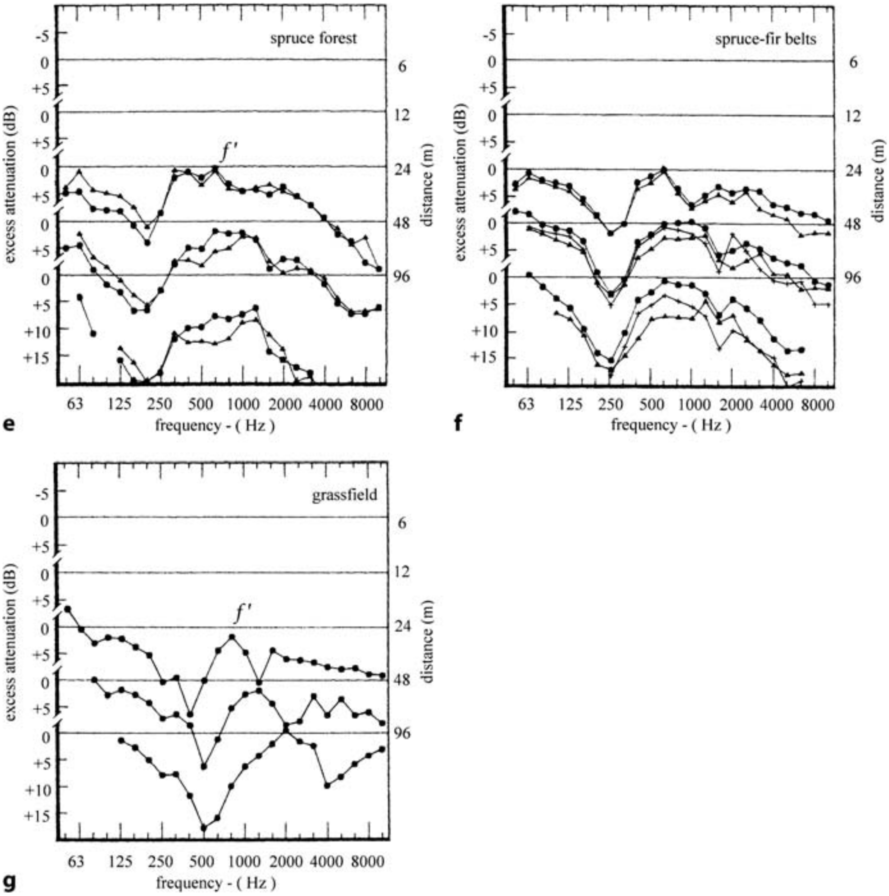

Fig. 4.44. (continued)

at the receiver of direct waves and reflected waves. Because of the complex distribution of reflecting surfaces in the forest, the variety of possible paths for the reflected waves causes an important distortion of transient sound waves.

The factors affecting reverberations are: the directivity of the source and receiver, the carrier frequency and the wavelength of the sound in relation to the dimension and shape of the scattering surfaces. Compared with low frequencies, reverberation increases for frequencies higher than 3 kHz, because of a greater scattering during sound transmission through forest. Reverberation has a masking effect for the long-distance transmission of sound, which can be observed through sharp changes in sound intensity, random amplitude fluctuations accumulating from nonstationary heterogeneities in the propagation medium and signal dispersion produced by numerous reflecting, refracting or diffracting objects. The directionality of the received low frequency sound is greatly degraded because of irregular amplitude fluctuations and signal dispersion. The increase in sound scattering and reverberation in forest is also produced by a large amount of stationary heterogeneities produced by micrometeorological instabilities. For animal communication in forest, reverberation imposes additional limitations related to the rate of repetitive frequency modulation (Wiley and Richards 1978).

Data on reverberation in a pine stand (a monoculture on flat ground, *Pinus nigra*, 29 years old, average diameter 16 cm, average tree height 11.20 m, tree density 0.19 trees/m^2, percent canopy cover 79%, canopy area 22 m^2, n = 0.19 trees/m^2, air absorption 0 dB) were provided by Huismann and Attenborough (1991). Reverberation was measured by switching the source on and off. Pink noise was used as the signal. The real-time analyzer measured a large number of one-third octave band spectra in its transient mode (Fig. 4.45). The decay curves measured at 1,000 Hz and 4,000 Hz at distance of 10 m and 100 m from the source showed that the curves coincide shortly after the moment that the source-off event reaches the 100 m receiver (after 320 ms). At the moment

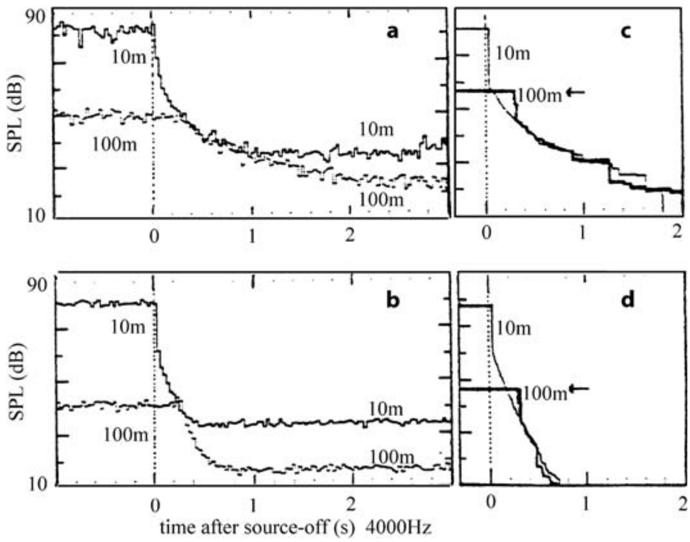

Fig. 4.45. Reverberation SPL at 4,000 Hz as a function of time after the source-off. Measured and modelled noise-off decay for 1 kHz and 4 kHz (Huisman and Attenborough 1991). Reprinted with permission from the Acoustical Society of America, copyright 2005. **a** Simultaneously measured source-off response at 10 m (*upper lines*) and at 100 m (*lower lines*), at 1 kHz. **b** Simultaneously measured source-off response at 10 m (*upper lines*) and at 100 m (*lower lines*), at 4 kHz. **c** Modelled source-off response that fit to experiments in **a**, air absorption 0 dB/s, effective scattering diameter 0.04 m. **d** Modelled source-off response that fit to experiments in **b**, air absorption 10 dB/s, effective scattering diameter 0.16 m

at which the switch-off event reached the receivers, a steep fall in the levels was observed, corresponding probably to the contribution of the reverberant sound field to the total sound field. The high-effective tree absorption at 4,000 Hz means that the nonlinearity of the decay curve almost disappeared (Fig. 4.45b).

Reverberation was measured both for its own interest and in order to obtain data on the scattering effect of vegetation, independent of ground effect and meteorology, using the model proposed by Kuttruff (1967). In this theoretical model, the trees are perfect cylinders and the forest is represented as an isothermal windless air volume without ground, containing a random array of infinitely long parallel cylinders which scatter sound particles from a point source.

Theoretically, the energy in the reverberant field in the pulse response is related to the direct field attenuation, to the total scattering attenuation and to the energy in the field, as shown by (4.16a), (4.16b).

$$A_{\mathrm{s}} = 10 \log \left[\frac{(E_{\mathrm{d}} + E_{\mathrm{r}})}{E_{\mathrm{f}}} \right] (dB) \tag{4.16a}$$

$$A_{\mathrm{d}} = 10 \log \frac{E_{\mathrm{d}}}{E_{\mathrm{f}}} (dB) \tag{4.16b}$$

Table 4.13. Insertion loss (dB) for barriers with different edge profiles (Ishizuka and Fujiwara 2004). Reprinted with permission from Elsevier, copyright 2005

Barrier and edge profile	Characteristics	Insertion loss	
		Mean value (dB) (IL)	Relative value (dB) (ΔIL)
Plain, rigid surface	3 m reference	15.2	0.0
	6 m	20.1	4.9
	10 m	23.4	8.2
Rectangular edge	Rigid surface	16.2	1.0
	Absorbing	19.7	4.5
	Soft	23.1	7.9
T-shaped edge	Rigid surface	17.1	1.9
	Absorbing	20.5	5.3
	Soft	23.6	8.4
Cylindrical	Rigid surface	14.7	−0.5
	Absorbing	19.2	7.6
	Soft	22.8	7.6
Double cylindrical	Rigid surface	17.9	2.7
	Absorbing	20.4	5.4
	Soft	23.3	8.1

where: A_s is the total scattering attenuation, A_d is the direct field attenuation, E_d is the energy in the direct field, E_r is the energy in the reverberant field and E_f is the energy in the free field.

As can be seen from Fig. 4.45, the measured nonlinear decay of levels with time seems to be consistent with the model proposed by Kuttruff. For quantitative calculations, the values of R_e (effective refraction factor) and D_e (effective

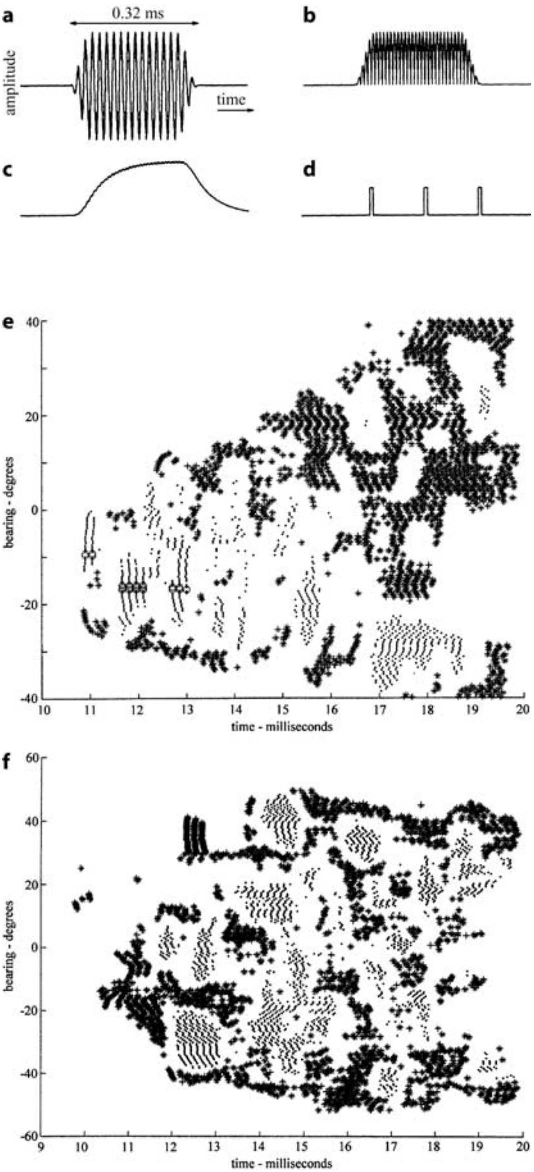

Fig. 4.46. Pseudo-action potentials produced by echo signal processing used for the identification *of Rhododendron maximum* and *Taxus media* (Kuk 2001). Reprinted with permission from the Acoustical Society of America, copyright 2005. **a** Simulated echo waveform stimulus, **b** half-wave rectified waveform–transmitter substance release, **c** output signal at lossy integrator–transmitter, **d** sequence of three pseudo-action potentials. **e** *Rhododendron maximum* located at 1.95 m range with mobile sonar and corresponding to the outputs of classifier neurons, deduced from a pseudo-action potential field produced by a scan plane tilted 35° downward from horizontal. **f** *Taxus media* located at 1.8 m range with mobile sonar and corresponding to the outputs of classifier neurons, deduced from a pseudo-action potential field produced by a scan plane tilted 35° downward from horizontal

trunk diameter) have to be obtained by fitting predictions to the measurements. Table 4.13 shows a good agreement between the theoretical and experimental data only for a limited number of data. The decrease in D_e with increasing wavelength is well comprehensible, but $R_e = 0.1$ is low.

From all these data, it seems clear that there are more phenomena than just scattering that influence sound transmission (ground effect, etc.). An important statement of the modelling proposed by Huisman and Attenborough (1991) is that "the important contribution of the direct field implies that the total attenuation due to scattering A_s can be approximated by the direct field attenuation A_d".

The information content of echoes from in situ plants and trees can be used for their identification (Kuc 2001), by transforming echoes into pseudo-action potentials for classifying plants, using conventional mobile sonar, with a narrow bandwidth of about 3 kHz, operating in metrology and mobile robot applications.

Specular plants, such as the rhododendron (*Rhododendron maximum*), have flat leaves that are large, compared to the wavelength, and act as isolated specular reflectors. The sonar response is characterized by large amplitude and coherence over successive echoes. Diffuse plants with needles, such as yew (*Taxus media*), act as diffuse scatterers and produce many small echo components, which superimpose randomly at the detector. This phenomenon is produced because needles are small compared with the wavelength. The information content of point process extracted from in situ measurements, through their characteristic pattern, also identified trees such as sycamore (*Platanus occidentalis*) of 17 cm diameter and maple (*Acer platanoides*) of 80 cm diameter. Figure 4.46a–d shows the echo processing to produce pseudo-action potentials. By rotating the transducers while emitting probing pulses and processing the echoes, the sonar forms a sector scan of the environment. From one emission, the signals have a temporal response; and from the sector scan, the signals have a spatial dimension. The echoes used as navigation landmarks were classified using delay and coincidence detection. The sequence for *Rhododendron maximum* is shown in Fig. 4.46e and those for *Taxus media* in Fig. 4.46f.

4.3.4 Atmospheric Conditions

Outdoor acoustic measurements are affected by the atmospheric conditions, relative humidity, temperature or wind gradients (Beranek 1971). The structure of the atmosphere varies with climate, weather, local conditions, diurnal cycles and insolation. All these factors influence sound transmission in a random way (Brown 1987). The sound speed profile under different meteorological conditions has been widely studied (Waxler 2004) for various applications including physical meteorology, community noise modelling, bioacoustics and forestry. The meteorological conditions have a screening effect on sound and noise transmission (Barrière and Gabillet 1998). The wind rustling sound emitted when vegetation rustles in the wind is perceived by humans as a comfortable sound. Yamada et al. (1977) noted that the rustling sound is very similar to white noise, having the same octave bands.

Inside the forest, wind speed and temperature gradient are reduced and, because of this, the total acoustical efficiency increases in the case of favorable propagation conditions. Wind penetrating direction has an important impact on wind speed in forest. In the trunk space, the wind speed is greater than in the canopy – variations of 45% and more can be expected (Raynor 1971). Huisman et al. (1988) reported data on temperature variation in a forest stand (Fig. 4.47) and noted that the crown layer is thermodynamically active. Near the ground, temperature effects are neglectable up to at least a distance of 100 m, because of the quiet isotherm air layer below the canopy. A ray tracing calculation could demonstrate that, depending on the shape and profile of the canopy, the sound refracted by the crown layer came down to a distance of a few hundred meters. Ohsato (1972) demonstrated the wind masking effect on a 2 kHz pure tone propagation in forest.

"In the forest, the effect of the fluctuating sound velocity profile in the late morning and the afternoon on sound transmission was clearly audible, especially if pure tones of chords were used as signals. The effect is an apparently random fluctuation of SPL of any single tone but with a variable amount of correlation between the various tones of the chord. These fluctuations can be large, for ex. at a distance of 100 m on a bright day; we monitored a change in level of a 4 kHz pure tone of 11 dB within a period of 50 s. With one-third octave band noise, these effects were less pronounced, which indicates that

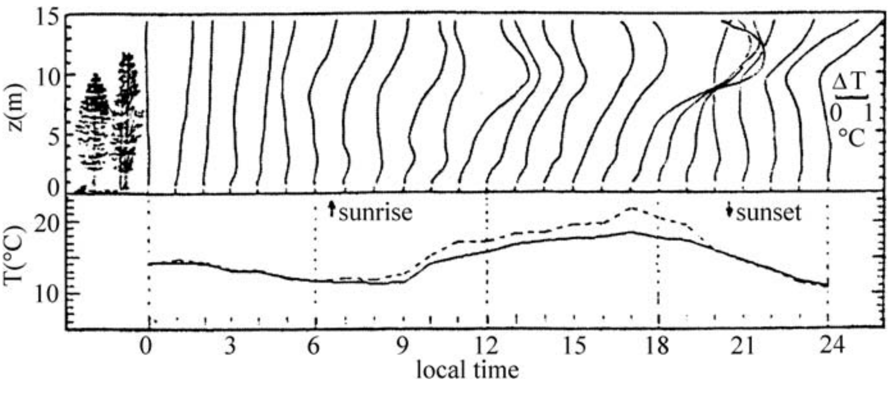

Fig. 4.47. Wind and temperature profiles during the day time (Huisman and Attenborough 1991). Reprinted with permission from the Acoustical Society of America, copyright 2005

interference plays a role" (Huisman and Attenborough 1991). This is a very valuable observation in forest, since it motivates subsequent investigations. Using a numerical simulation of wind and sound propagation through an idealized stand of trees, Heimann (2003) demonstrated that direct attenuation by trunks (produced by multiple reflections and scattering) is much larger than indirect attenuation, which is due to a reduction of the vertical wind gradient in the stand.

A comparison between winter and summer measurements in different forest sites allowed an assessment of the effect of season and foliage on sound attenuation (Price et al. 1988). The attenuation is significantly less in winter, because of the absence of leaves. A peak of attenuation observed at 200 Hz is attributed to the ground effect; and the gradually increasing attenuation for frequencies higher than 1 kHz is attributed to scattering both by trunks and by foliage (see previous Fig. 4.19).

Relative humidity affects the properties of all porous materials and consequently the impedance of the ground and the absorption and scattering by trunks, foliage or bark. The effect of relative humidity on attenuation in a pine plantation is shown in Fig. 4.48 over a period of 2 months (during which time no rain was recorded). It appears that the relative humidity of the atmosphere has a very important effect on the measured attenuation rates, at all frequencies. The maximum attenuation rate occurs at about 75% relative humidity.

Atmospheric absorption as a function of relative humidity is shown in Fig. 4.49. The variations in the absorption coefficient expressed in dB per 100 m at normal atmospheric pressure and 20 °C are due to molecular absorption

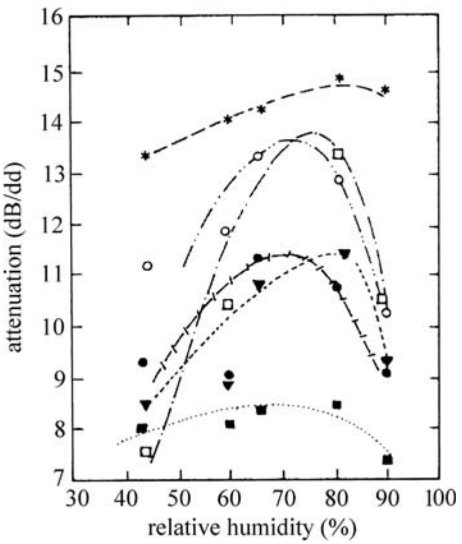

Fig. 4.48. Effect of air relative humidity on attenuation in a pine plantation for different frequencies (Fricke 1984). Reprinted with permission from Elsevier, copyright 2005. *Circles* 31.5 Hz, *black squares* 125 Hz, *black circles* 500 Hz, *black triangles* 1 kHz, *white squares* 2 kHz, *stars* 4 kHz

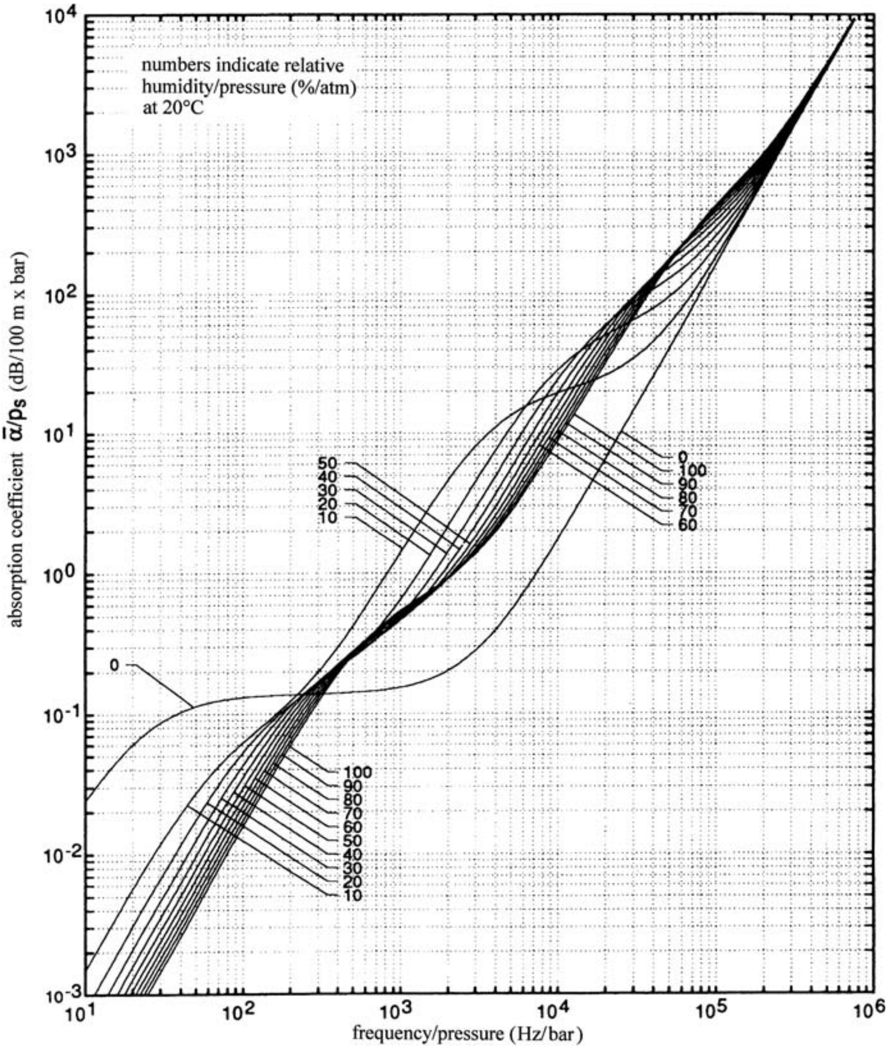

Fig. 4.49. Air relative humidity in air due to molecular absorption at 20 °C. The *ordinate* gives the rate of conversion of sound energy into heat during sound propagation and is expressed in dB/100 m. The *abscissa* is the ratio between the frequency from 10 Hz to 1 MHz and the pressure (Hz/atm; Bass et al. 1995). Reprinted with permission from the Acoustical Society of America, copyright 2005

and depend on pressure. The molecular absorption of oxygen and nitrogen molecules converts a very small fraction of the acoustic wave energy. Above 500 Hz, the predominant mechanism is related to the oxygen–water vapor molecular relaxation. This mechanism induces an attenuation of 2 dB/km. This attenuation can increase with frequency. Below 500 Hz, the nitrogen–

water vapor relaxation is observed, producing less energy absorption then the oxygen–water vapor relaxation (Embelton 1996).

For a better understanding of the complex phenomena related to sound propagation in a forest, modelling and simulations must be used. For this purpose, several acoustical parameters such as attenuation, reverberation and echoes can be used. Acoustically relevant characteristics of a forest are: tree species, trunk diameter, number of trees/unit surface, scattering and absorbing cross-sections, leaf area, mean free path length, visibility and light penetration path. The propagation of sound through an idealized stand of trees was modelled by Heimann (2003) in 3-dimensions, using a numerical finite difference time–domain fluid mode, with the discussion concentrated on attenuation. Systematic simulations performed by varying the number of trees/unit surface and the trunk diameter showed that the simulated attenuation by the trunks agrees with scattering theory. Direct attenuation by the trunks through multiple reflections and scattering is much larger than indirect attenuation due to the reduction of the vertical wind gradient in the stand and the corresponding reduction in acoustic wave refraction.

4.4 Sound Scattering by Barriers

4.4.1 Psychological Effect

The variability of individual responses to a given noise exposure is remarkably high. There appears to be a widespread popular belief that belts of trees can cause an important reduction in traffic noise (Watts et al. 1999). Survey respondents residing close to roads express the wish that bands of trees should be used to screen traffic noise along departmental roads. All over the world, owners plant hedges or trees in their gardens to screen traffic noise. Huddart (1990) measured a reduction of 6 dB(A) produced by a densely planted belt of trees 30 m thick, compared with grassland of the same thickness. Perfater (1979) noted that, when existing vegetation along a road was replaced by a solid barrier, the residents clearly felt that the vegetation had given better noise reduction. It seems that, sometimes, the effect related to the attractive visual appearance is predominant over the effective acoustical benefit.

It was proved that, when the ambient noise level was held constant (a single tone at 500 Hz which was varied between 50 dB and 80 dB and replayed through headphones), the loudness increased as the percentage of vegetation increased (Mulligan et al. 1987). This psychological effect can be explained by the fact that, when the source is visually screened, a listener expects its loudness to be significantly diminished.

Aylor and Marks (1976), using a white noise source limited by filters to a one-third octave band centered at 1,000 Hz, with a sound pressure level variable between 40 dB and 100 dB, found that a thick conifer hedge or louvered barrier with gaps (which allowed the direct transmission of sound but which completely obscured the source) produced similar sensitivities. When the source was visible either through an open-slat fence or where there was no screen at all, sensitivities were significantly lower. The difference at 65 dB sound pressure level for the open fence and conifer hedge was 7.5 dB; and for conifer hedge and no screen, the difference was 3.5 dB. It was noted that the effect was purely visual and was not due to the differences in the frequency spectra of noise transmitted through or diffracted over the different barriers. These effects are comparable with the differences reported by Watts et al. (1999) between a willow barrier, metal barriers and without a screen.

Aylor and Marks (1976) blindfolded a sample of listeners. They were not able to observe differences in the ratings produced for the different listening conditions.

Watts et al. (1999) demonstrated that the presence of vegetation between the source and receiver had little effect on the sound spectrum, but the noise barriers reduced the levels at higher frequencies. The A-weighted level was not an adequate measure of noise exposure, since it might have failed to reflect these differences in the spectral balance. A more sophisticated parameter which takes account of such changes is the loudness level.

If the rate of the attractiveness of the barriers is scaled from 0 to 9, where 0 corresponds to "very unattractive" and 9 corresponds to "very attractive", a metal barrier 15 m long and 3 m high is rated at 2 and a woven willow vegetative noise barrier with earth fill, of the samesize, is rated at 7. This was not apparent from the noise sensitivity results. It was supposed that the willow barrier effect was perceived through the well known "halo" effect and it was concluded that, in this particular case, the effect of vegetation on noise sensitivity was associated with the degree of visual screening of the source. Noise reduction is small unless the vegetation belt is wide.

4.4.2 Solid Barriers Without Vegetation

Solid barriers reduce noise in two ways, by reflecting or absorbing noise. Reflecting barriers are build of any dense material. Absorbing barriers have a perforated skin and a chamber behind, into which the sound waves are dispersed. The simplest environmental barrier is the earth mound. The architectural morphology of barriers must be integrated into the local landscape. The good design of environmental barriers must take into consideration solid materials as well as the plants which help to integrate barriers into their surroundings, reducing their apparent scale and softening their appearance by providing robust features.

The most common noise barrier is composed of a single vertical screen which obstructs the propagation of sound from source to receiver. Adding side panels to this profile or using two or more screens could be considerably more efficient in terms of noise reduction.

The field performance of noise barriers has been evaluated for more than 30 years (Raynor 1971; Scholes et al. 1971; DeJong and Stusnick 1976; Reethof and Heisler 1976; Watts et al. 1994; Jimenez-Altamirano 1997; van Renterghem and Botteldooren 2002, 2003).

Classic barrier modelling in a homogeneous atmosphere is shown in Fig. 4.50, in which the diffraction sound path around corners over wide barriers is traced. The barrier insertion loss prediction provides an accurate means

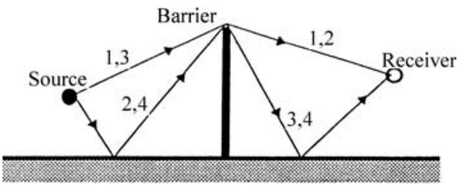

Fig. 4.50. Diffraction path induced by the simplest noise barrier (Muradali and Fyfe 1999). Reprinted with permission from Elsevier, copyright 2005

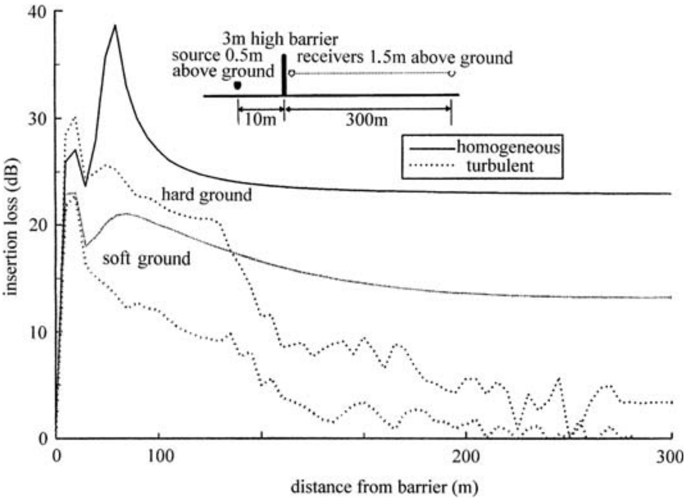

Fig. 4.51. Theoretical insertion loss produced by a barrier of 3 m height, at 500 Hz for asoft and hard ground (Muradali and Fyfe 1999). Reprinted with permission from Elsevier, copyright 2005

to consider reflection, diffraction and phase interference in the sound field around the barriers.

Figure 4.51 shows the insertion loss as a function of distance for a 3 m barrier height over rigid and soft ground in a homogeneous and turbulent atmosphere. It can be seen that the insertion loss is lower for the soft ground case. The sound absorption expressed by the insertion loss greatly deteriorates after about 75 m which means that, after this distance, the rays that pass over the barriers negate most of the barrier shielding.

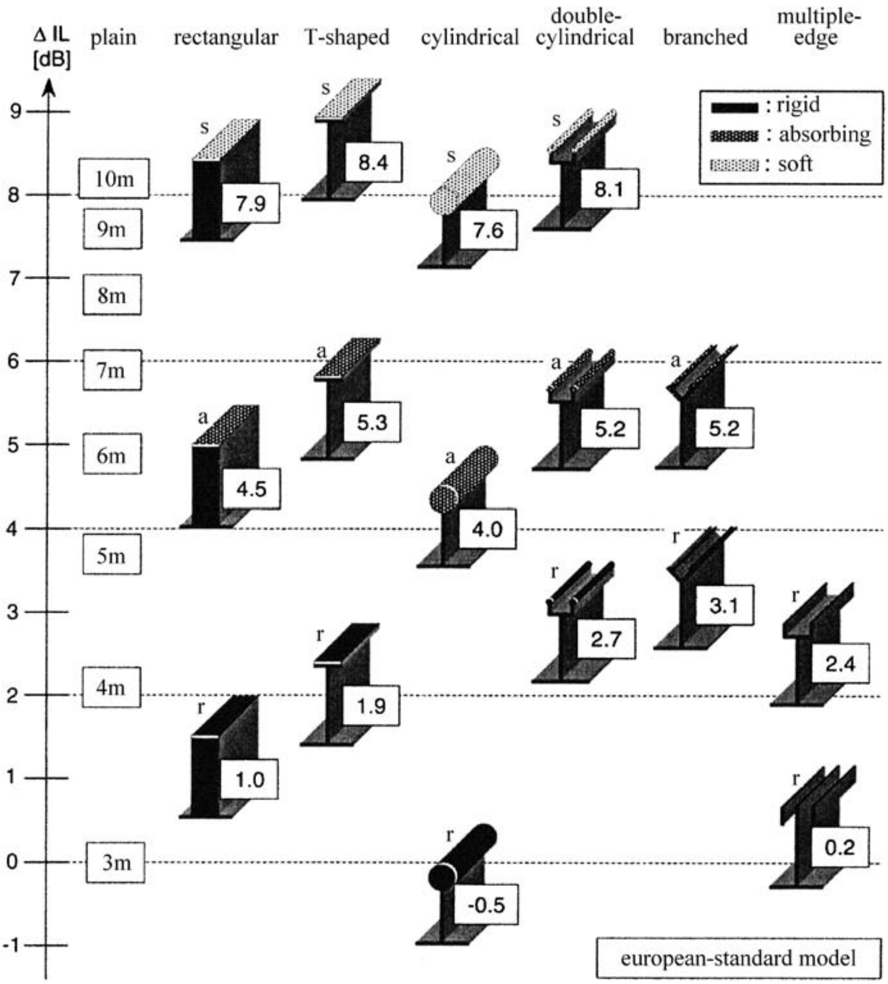

Fig. 4.52. Comparison of the performance of barriers (ΔIL in dB) with various shapes (plain, rectangular, cylindrical, etc.) for the European standard model (Ishizuka and Fujiwara 2004). Reprinted with permission from Elsevier, copyright 2005

Several technical solutions exist for improving the acoustical performance of plain barriers, such as modifying the shape by introducing two or more diffracting shaped edges or by suppressing the sound pressure at the edge by installing a soft absorbent material and decreasing the diffracted field behind. The shaped edges of noise barriers are very complex and can be T-shaped, cylindrical, double-cylindrical, branched, multiple-edged, or with side panels (Ishizuka and Fujiwara 2004). Figure 4.52 shows a comparison between the performance of barriers with various shapes for the European standard noise source model EN 1793-3. The reference is a 3-m high plain barrier which is compared with plain barriers of different heights varying from 0.2 m to 8.0 m. All tested barriers had a maximum width of 1 m. The mean insertion loss (*IL*) was measured for a broadband noise spectrum under the "shadow" region of the barrier. The losses were measured at six positions and averaged. The efficiency of barrier shape for three surface conditions (rigid, absorbing, soft) was expressed by ΔIL, which is the difference between the tested barrier and the reference plain barrier of 3 m height. Data from Table 4.13 show the important efficiency of rectangular, cylindrical and double-cylindrical barriers, for which ΔIL is between 7.6 dB and 8.4 dB.

The acoustical performance of noise barriers can be determined using different techniques, such as diffraction techniques based on geometrical ray theory, boundary element method, finite element method and finite wave envelop method.

The reader interested in these theoretical methods can refer to Crombie et al. (1995), Duhamel et al. (1998), Muradali and Fyfe (1999).

4.4.3 Solid Barriers with Vegetation

Along many road corridors, the introduction of environmental noise barriers which fit with the local environment was effective with the introduction of noise legislation. This integration into the local landscape or townscape can be achieved by planting with different species and in this way can soften the appearance of the barrier by breaking the scale of observation. Figure 4.53 shows the increasing attenuation induced by the combined action of trees and barriers.

The simplest effective environmental noise barrier is the earth mound. A comparison between the land-take for a 4 m high earth mound and a 4 m high bio-barrier is given in Fig. 4.54. The bio-barrier needs a space only 2.5 m wide, while the earth mound is positioned on a space 14 m wide. Planting with vertically oriented species like for example *Parthenocissus quinquifolia* does not require a large amount of space (30 cm) and improves the appearance of the barrier. For woody plants, 1 m is required (Kotzen 2004).

Bio-barriers which incorporate planting within their structure are shown in Fig. 4.55. Following their shape, these bio-barriers are classified as:

1. A-frame barrier, having an internal tie, with the plants affixed by rubber straps;
2. Vertical barriers on timber supports and rubber straps;
3. Box wall, on a steel support and appropriate foundations, a welded steel grid, with a horizontal strut and an irrigation pipe;
4. willow-weave wall on a geogrid and ropes;
5. stack with steel and concrete struts and the planting medium inside the structure.

The materials and technical solutions used for different barriers are shown in Fig. 4.56. Planting behind and back to the working face of the barriers is always important for perfect integration of the barriers into the landscape. The skilful design of planted barriers is an outstanding example of acoustic ecology, encouraging a deeper appreciation for noise and its role in our lives.

A combined effect on excess attenuation of a barrier (2 m height) and belt of trees is shown in Fig. 4.57, for traffic noise on an asphalted road. A reduction of about 3 dB(A) can be observed in a zone between 100 m and 450 m distance from the source and 1,030 m height, probably due to the canopy. The iso-excess

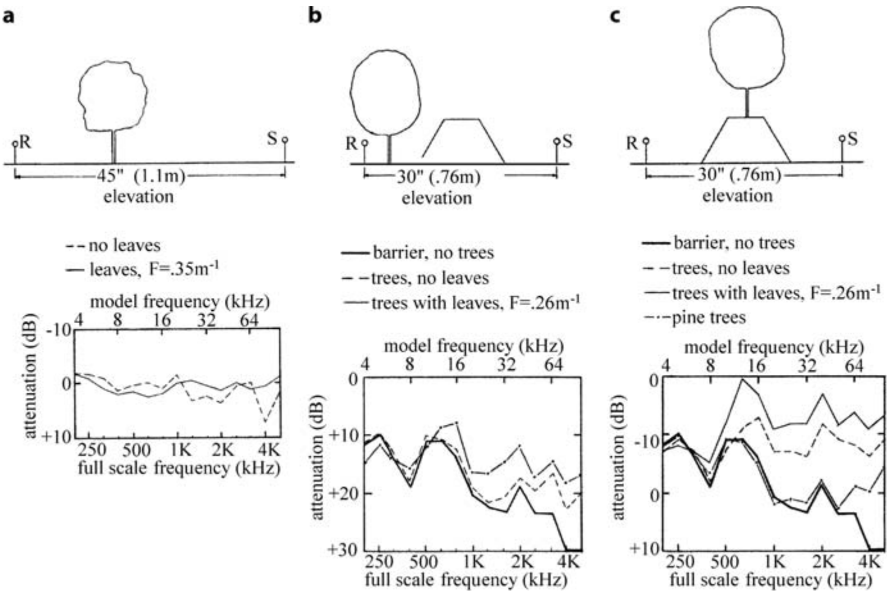

Fig. 4.53. Excess attenuation barriers and trees. **a** Tree on a flat plain case, **b** barriers with trees along the side, **c** trees on the top of the barrier (Lyon et al. 1977)

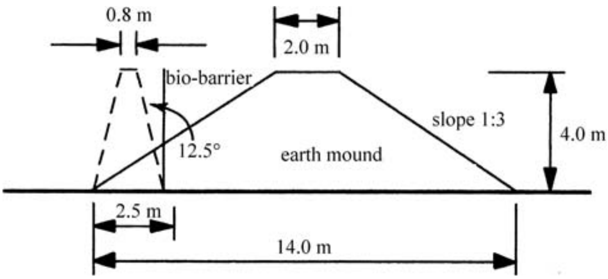

Fig. 4.54. Comparison between bio-barrier and earth mound of the same height (4 m) and of different wide (2.5 m for the bio-barrier and 14 m for the earth mound; Kotzen 2004)

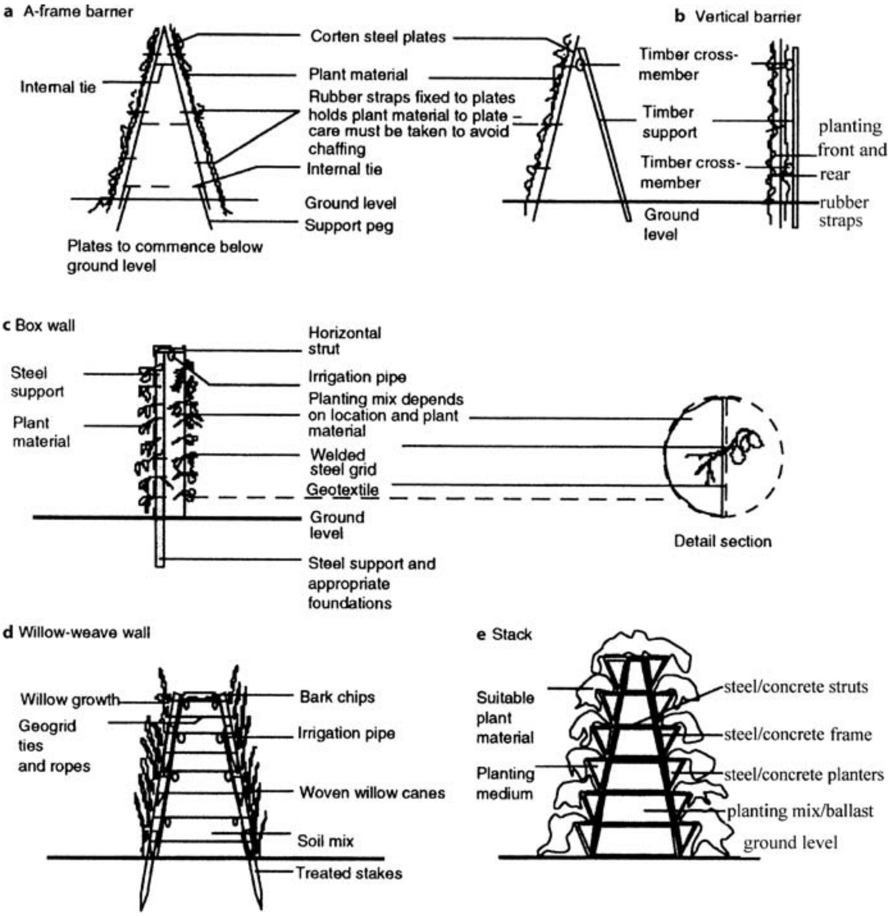

Fig. 4.55. Bio-barriers incorporating planting (Kotzen 2004). Different types of barriers: **a** A-frame barrier, **b** vertical barrier, **c** box wall, **d** willow-weave wall, **e** stack. Materials used are timber, concrete, earth

attenuation of 2 dB(A) between 100 m and 600 m is probably produced by the scattering of trunks. Under the canopy, between about 1 m and 6 m height, the iso-excess attenuation is very low (less then 1 dB). The barrier effect (4 dB) can be seen at 300 m distance from the source.

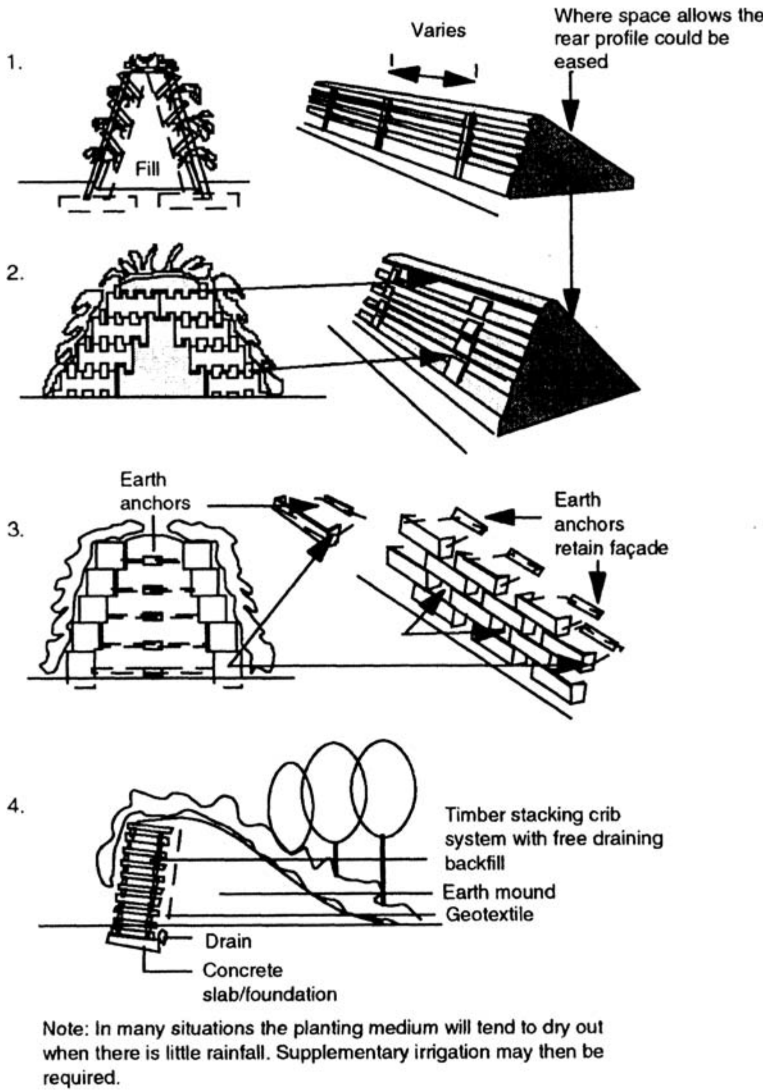

Fig. 4.56. Different materials (timber, concrete, earth) used for bio-barriers (Kotzen 2004)

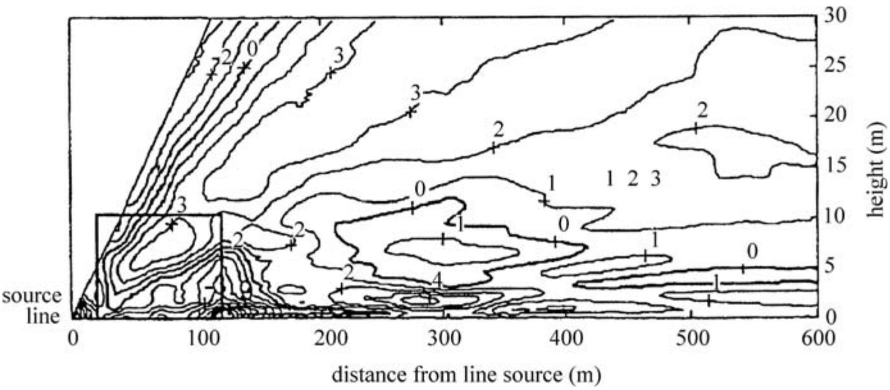

Fig. 4.57. Iso-excess attenuation curves [dB(A)] as a function of the distance from the line source and the height of the trees (Barrière and Gabillet 1998)

4.5 Summary

Plants in general can attenuate sound by reflecting and absorbing energy. Sound transmission by plant material, namely trees, tree belts and forest stands, is expressed as excess attenuation, i.e. the measured sound pressure level corrected for air absorption, minus the free-field level. The free-field level is the level that would exist if there were no obstacle and no sound velocity gradient. The attenuation properties of vegetation are questionable because of the great number of variables involved. Certain types of vegetation are better for attenuating sound than others. A valid comparison between the performances of different types of vegetation cannot be made without an exact description of the methodological factors characterizing the noise source and the receiver, such as height, placement of source (whether inside forest or outside and, if outside, how far outside) spectrum of source and its duration (steady or transient), size and density of trees and atmospheric conditions during experiments (temperature and wind gradients, relative humidity; Table 4.14). The ground is a significant absorber of sound in forest. The soft forest floor has a pronounced influence on low-frequency sound propagation. An excess attenuation of 6 dB per doubling of distance is shown to be possible.

Acoustic characteristics of the constitutive elements of the tree, such as trunk, bark and canopy, and of the forest floor should provide needed insight into the acoustic absorption mechanisms. An acoustic wave of 1 kHz frequency propagates with a wavelength comparable with the trunk diameter. The trunk, branches and foliage partially scatter the incident acoustic energy. Scattering effectiveness is consistent with the geometry of the scatterers, the bigger the scatterers, the lower the frequency at which the scattering phenomenon be-

Table 4.14. Effects of soil, trunks, foliage, meteorology and topography on excess attenuation

Effect	Characteristics		Excess attenuation	References
	Acoustic	Other	Frequency	
Soil	Impedance	Width	Positive 100 – 500 Hz Negative at 1 kHz	Attenborough (1985)
Trunks	Scattering	Diameter, density/m^2	1 dB at 300 Hz 2 dB at 1 kHz 4 dB at 10 kHz	Embelton (1966), Price et al. (1988)
Foliage	Scattering and absorption	Biomass, leaf size		
Meteorology	Sound speed	Temperature, humidity	3 dB at 5 kHz, 10 dB at 10 kHz, at 100 m, 20 °C	Bass et al. (1995), Attenborough et al. (1995)

comes effective. The audible reverberation in a forest can be explained by the interference between direct and ground-reflected sounds and the scattering effects induced by trees, branches and meteorological conditions. Modelling and simulation can be used for a better understanding of the complex phenomena related to sound propagation in a forest. For acoustics, the relevant characteristics of a forest are tree species, trunk diameter, number of trees/unit area, scattering and absorbing cross-section, leaf area, visibility and light penetration path.

Sound scattering by belt of vegetation and barriers is largely used for reducing traffic noise by reflection and absorption. The skilful design of barriers is an outstanding example of acoustic ecology, encouraging a deeper appreciation for noise and its role in our lives.