We are IntechOpen, the world's leading publisher of Open Access books
Built by scientists, for scientists

6,100
Open access books available

150,000
International authors and editors

185M
Downloads

154
Countries delivered to

Our authors are among the
TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

WEB OF SCIENCE™
Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Chapter

Evaluation of Industrial Noise Reduction Achieved with a Green Barrier: Case Study

Martha Cobo Dorado, Gissell Rodríguez Milan and Alice Elizabeth González

Abstract

In this chapter, a case study is presented on the evaluation of acoustic performance of a tree barrier. It is a eucalyptus barrier that was planted as a visual barrier to block an industrial plant. First, the depletion law of sound pressure levels (SPL) of the source was analyzed; a linear divergence was found. A calculation scheme similar to that of ISO 9613-2 was applied. When comparing the SPL measured at a specific receiver with the results of propagating the SPL from the source without considering the existence of the barrier, an extra attenuation of 12 dB appeared, reinforcing the idea that the plantation behaves as an acoustic barrier. Four different calculations were used to obtain its insertion loss (IL), including general equations and expressions developed for green barriers. The best fit was obtained using equations for solid barriers, although it was not the expected result. This finding could be explained by the great distance between the source and the receiver. It opens the possibility of successfully using IL prediction equations for solid acoustic barriers (both thin and thick) to estimate the acoustic performance of green barriers, at least under conditions similar to those of this case study.

Keywords: noise control, green barriers, acoustic barriers, industrial noise control

1. Introduction

This case study is based on postgraduate research by Cobo Dorado [1]. It refers to a limestone calcination plant to produce powdered lime, which is located in a rural area. The industrial plant has dense forest areas in parts of its perimeter, which were planted for landscape purposes.

The main sources of noise in the plant are the crushers, the sifter, and the coal processing mill. The latter is the object of this study.

There are four receivers on the perimeter of the property where the sound pressure levels (SPL) are regularly measured; two of them, called P1 and P2, will be considered for this study.

One of the main discussions regarding barrier options to mitigate the effect of noise caused by industrial plants is whether the plant barriers such as eucalyptus plantations could effectively behave as acoustic barriers. Thus, the goal of the study was to evaluate if the presence of a eucalyptus plantation located between the coal processing mill (sound source) and P1 collaborates on reducing the SPL in P1. The main objectives were finding the best fit for the depletion law of the main noise source to better evaluate the acoustic behavior of the tree barrier comparing the accuracy of the results achieved by using four different equations to calculate the insertion loss (IL) of the green barrier under study and concluding about the possibilities of using general equations for obtaining the IL of a green barrier.

In order to carry out this research, measurements of SPL were taken, based on protocols of the National Environmental Authority. All measurements were taken with time weighting Fast at the sonometer, at a height of 1.5 m above the ground. They had a minimum duration of 15 minutes. The measurements on different days were considered.

A set of SPL measurements taken when the coal mill was the only operating source was selected. The measurements in the receivers were taken monthly. The equivalent continuous SPL (L_{eq}) was recorded each second in scale A ($L_{AF,eq}$), in scale C ($L_{CF,eq}$), and in octave bands ($L_{ZF,eq}$). The background SPL at P1 and P2 were measured during the shutdown of the plant, and their frequency spectra were also obtained.

Based on the literature review (see Section 2) and the general characteristics of the eucalyptus plantation, it appears that it could attenuate the SPL in P1.

This paper is structured in six sections. First, a theory background (Section 2) and the case study basic information (Section 3) are presented; all the relevant measured spectra are also shown in Section 3. Section 4 points out the applied methodology. Section 5 presents the calculation process; at first, the sound depletion law of the source was studied and then, the SPLs in the receiver P1 were found without studying the green barrier. For explaining the difference between the measured and calculated figures, the acoustic performance of the tree plantation was obtained four ways: two of them were for solid acoustic barriers and the other two for tree barriers. The last sections for this chapter are devoted to discussing the results and present our conclusions.

2. Background

Acoustic barriers have been widely used when noise control on the propagation path is needed, once there are no other possibilities of control on the source [2]. Up to five acoustic phenomena can occur in an acoustic barrier: sound reflection, transmission, absorption, diffraction, and scattering.

The material of the surface exposed to the source is what defines the amount of acoustic energy that will be scattered, absorbed, and reflected. When there are barriers on both sides of a source and their surface materials are not adequate for sound absorption, sound pressure levels may increase due to multiple reflections between the two sheets of the acoustic barrier [3]. The acoustic impedance of the material of the barrier determines the amount of acoustic energy that will be transmitted through it. It is generally assumed that if a material has a surface density of at least 10 kg/m^2 (kilogram per square meter), it is suitable for acting as a noise barrier [2].

Finally, diffraction should be the predominant acoustic phenomenon in a barrier. It refers to the fact that sound waves change direction, edging the obstacles they find in their path, which, in the case of a barrier, occurs at the top edge but also at the side edges [2].

The attenuation provided by an acoustic barrier is called *insertion loss* (IL), which is defined as the difference between the direct sound pressure level obtained in the absence of an acoustic barrier (L_{dir}), and the level obtained with the presence of the barrier, i.e., the diffracted sound pressure level (L_{dif}) [2] (see Eq. (1)).

$$IL = L_{dir} - L_{dif} \tag{1}$$

The proposal of Maekawa to calculate the IL value from the Fresnel number N marked a milestone in the development of noise barrier research (Eq. 2). A detailed analysis of Maekawa's work can be found in [4].

$$\text{IL} = 10 \ \log \ (20 \ \text{N}) \tag{2}$$

where $N = \frac{2\,\delta}{\lambda}$ is the Fresnel number

λ = the wavelength of sound (in meters) at the considered frequency f, and.

$\delta = a + b - d$ is the difference between diffracted sound path and direct sound path (in meters) (see **Figure 1**).

Since Maekawa's first approach had some limitations, some authors have worked on finding a better calculation method to predict the IL of acoustic barriers [2]. In next sections, some of them will be presented.

2.1 Thick barrier approach

An acoustic barrier is said to be "thick" when it has more than one point where diffraction can occur [2].

A barrier is considered thick when:

- The width of its crest exceeds 3 m. In this case, it is considered to be thick for all frequencies. Although not exactly a crest, the width of the straight line that connects the source and receiver.

- The wavelength λ to be considered is less than 1/5 of the crest width t ($\lambda < t/5$). If there were frequencies where this relation is not accomplished, the barrier would function as a thin barrier, and it should be calculated in such manner.

Eq. (3) can be used for solid barriers either thin or thick. In the case of thick barriers, the thickness t is added to the smallest of the distances a or b and with this

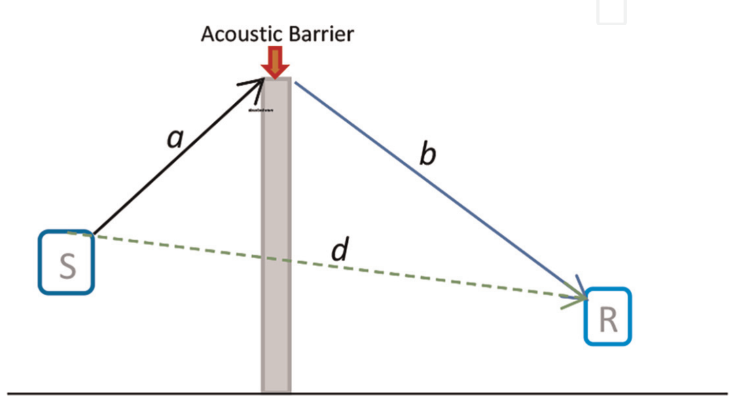

Figure 1.
Cross section of an acoustic barrier (adapted from [2]).

new value *a'* or *b'*, the Fresnel number N should be calculated. Then, the insertion loss will be obtained through Eq. (3) [2].

$$\mathrm{IL} = 10\ \log\ (3 + 10\ \mathrm{N} \cdot \mathrm{K}) - \mathrm{A_{gr}} \tag{3}$$

Where:

N: Fresnel number calculated by considering the hypothesis of thick barrier, Eq. (4) (see **Figure 2**):

$$N = \frac{2}{\lambda}(a' + b - d) \tag{4}$$

For a thick barrier, the value of *t* must be added to the minimum of *a* and *b*; the values corrected this way are noted as *a'* or *b'*.

K: meteorological correction, with.

K = 1 for distances between source and receiver either less than 100 m or greater than 300 m.

Otherwise:

$$K = e^{-0.0005\sqrt{abd/N\lambda}}$$

$\mathrm{A_{gr}}$: ground attenuation along the sound path.

The barrier attenuation should not be assumed to be greater than 20 dB.

2.2 Kurze-Anderson approach

This way of obtaining IL is a general one. The expressions to be used are those of Eq. (5) [2].

$$\text{If N} > 12.5 \qquad IL = 24$$

$$\text{If } -0.2 < \mathrm{N} < 12.5\ IL = 5 + 20\ log\ \frac{\sqrt{2\pi N}}{\tanh\sqrt{2\pi N}} \tag{5}$$

Where N is the Fresnel number defined in Eq. (4)

$$\text{Remember that } tanh\, X = \frac{senh\ X}{\cosh X} = \frac{e^X - e^{-X}}{e^X + e^{-X}}$$

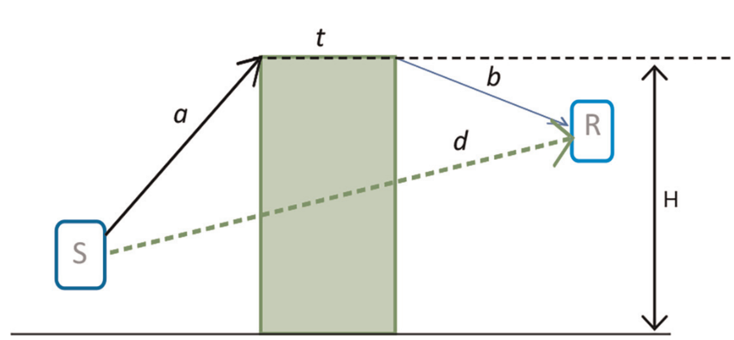

Figure 2.
Cross section of a thick barrier (adapted from [2]).

2.3 Green barriers

The case of tree or green barriers is rather different. Just as in "conventional" barriers, the hermeticity of the material is central, it is necessary to assume that the tree barriers are non-soundproof. In turn, scattering may homogenize the acoustic field into the tree plantation. On the other hand, among the characteristics of the vegetation that participate in the attenuation of the barrier, the density of the plantation, distance between trees, geometric pattern of the plantation, the features of trunks, bark, and canopy, and the dimensions of the leaves, whether the trees are deciduous or evergreen. The abovementioned points are presented in Section 2.3.1.

One simple point for expecting a good sound attenuation performance in a tree barrier is that it must block the visuals between source and receiver, as stated by ISO 9613-2 [5]. If the receiver is able to be seen from the source and through the vegetation, it is most probable that the barrier will not be dense enough for sound attenuation.

2.3.1 An overview of the research on green barriers

The acoustic of forests began to be studied in 1946 by Eyring [6], who found an attenuation of 0.05–0.13 dB/m (decibels per meter), increasing with frequency. Some years later, Embleton [7] and Aylor [8, 9] continued with Eyring's work. Embleton [7] obtained an important depletion of 7 dB/100 ft. (decibels each 100 feet) for frequencies below 2000 Hz. He tried to explain such high results thinking about branches as resonance absorbers, but his theory was not easy to be proven. Recent works, as Johansson's [10], show that the forest is a complex system that can reduce (absorb) or amplify sound pressure levels, depending on the phenomena that are activated for each case.

Aylor [8] showed that plants have a good behavior for noise control. He worked with pink noise attenuation through a dense reed marsh (*Phragmites communis*). The average height of the reeds was 2.5 m, the area of leaves per volume unit of canopy was 3.0 m^2/m^3, and the density of plants was 59 ± 10 plants/m^2. The average width of the leaves was 3.2 cm. Aylor found an increasing attenuation between 500 Hz and 10,000 Hz, with an increasing rate close to 4–4.5 dB/octave. He found an attenuation close to 18 dB at 10,000 Hz for 12.2 m broad of reeds. When comparing with corn plants (*Zea mays*) attenuation, he found that the best performance was at a frequency of 2000 Hz; the width of the corn plants leaves was 7.4 cm in average. In another study, Aylor [9] measured the sound attenuation related to trunks and stems. He used field corn (*Z. mays*), hemlock (*Tsuga canadensis*), red pine (*Pinus resinosa*), and a hardwood brush of about 6 m in height. He found the denser the plantation and the greater the leaves surface, the better the attenuation. Also, the trunks have an important effect on sound scattering, whether the wavelength was small in comparison to the radius of the trunk.

Price et al. [11] measured and studied different forests sound attenuation: Norway spruce (*Picea abies*) and oaks, with a dense undergrowth; a monoculture of Norway spruce of 11–13 m in height; a coniferous plantation including red cedar (*Thuja plicata*), Norway spruce, and Corsican pine (*Pinus nigra*). Summer and Winter measurements were performed. A general attenuation pattern was found, with a first absorption peak at about 250 Hz; a region of poor absorption performance and possible resonant amplifying, around 1000–2000 Hz; and a second attenuating region, from 2000 Hz to 10,000 Hz approximately. The authors aimed to build a predictive model, by adding the contributions to sound attenuation of ground, trunks, and foliage, calculating each one separately. On the other hand, Lee et al. [12] examined 15 sites with coniferous trees, along some roads in Virginia, USA. They concluded that only a very poor sound attenuation could be attributed to the trees. They found no differences according to the trees age, height, species, nor density at the sites.

Huddart [13] stated that noise barriers such as walls, fences, or mounds of earth are often used to reduce noise pollution from traffic, but that a tree belt would be a more environmentally friendly and esthetic option. He measured the attenuation of traffic noise through five types of vegetation up to a depth of 30 m. He verified that the foliage is important in reducing the high frequencies (above 2000 Hz), while the middle frequencies (250–500 Hz) are attenuated by the absorbent qualities of the ground. The ground absorption features can be enhanced by the roots of the plants and litter.

Huisman and Attenborough [14] showed that the acoustic response of a forest directly depends on the type of wave interference: for constructive interferences (coherent waves), sound reverberation is expected; otherwise, attenuation of the sound may occur. The authors stated that sound scattering by atmospheric turbulence is a well-known phenomenon, related with loss of coherence of waves, for wavelengths minor than the trunk diameter.

Alessandro, Barbera and Silvestrini (1987) and Stryjenski (1970), cited by Ochoa de la Torre (1999) [15], proved that the acoustic absorption of some plant species varies with the size of the leaves and the density of the foliage. Thus, noise levels decrease should only be expected for frequencies above 2000 Hz, with attenuation values of 1 dB every 10 m of depth, up to a maximum of 10 dB at 100 m or more. Furthermore, Ochoa de la Torre (1999) cites Cook and Haerbeke (1971) and Alessandro et al. (1987) that, among other conclusions, stated that: "*a screen placed close to the source is more efficient than another next to the area to be protected*"; and that "*the species to be used must be evergreen, avoiding conifers, which are the least efficient.*"

In the same direction, Tarrero (2002) [16] cites Martens and Huisman (1986), who showed that deciduous trees attenuate more than grass without trees but less than evergreen ones.

In 2002, Tunick [17] linked meteorology and sound propagation in a forest. He found a microclimate, where temperature and wind velocity are rather uniform. The main attenuation phenomena in the forest are: interfering between sound waves, both direct and reflected on the ground; scattering and absorption by ground, trunks, branches, and atmospheric turbulence. In the range of medium frequencies (250–500 Hz), ground impedance is one of the most influencing factors. For frequencies from 1000 Hz to 2000 Hz, the trunks, branches, and canopy are the main agents, acting both by sound scattering and sound absorption. For these high frequencies, these phenomena seem to have more incidence on sound attenuation than refraction effects related to the microclimate in the forest.

Martínez Sala et al. [18] carried out a study with vegetable plantations (poplars, cypresses, laurels, and orange trees), demonstrating that it is possible to improve the sound attenuation obtained from a mass of trees if their elements are ordered in a periodic way. They worked with an arrangement in regular rows, a square, rectangular, and triangular configuration of the trees. Their experimental results showed that the highest sound attenuation was obtained for a range of frequencies related to the periodicity of the array. This behavior led them to intend that these sets of trees can be seen as sonic crystals. The experimental results showed that a belt of trees organized in a periodic matrix produces attenuation peaks at low frequencies ($f < 500$ Hz), not as a consequence of the ground effect but as a result of the destructive interference of scattered waves. Therefore, these periodic arrays could be used as plant acoustic screens.

Onuu [19] found that grass can introduce an attenuation in all frequencies twice the amount of attenuation of a forest. The best performance was measured between 1000 Hz and 4000 Hz. He also stated that the best relation for representing the attenuation of grass is logarithmic, whether for trees is a power equation.

Swearingen and White [20] proposed an adjustment of the calculation method of Defrance, to include other atmospheric phenomena, especially those related to scattering. As that previous model did, they used the Green's function parabolic equation (GFPE) for modeling different phenomena that they also measured. The authors added those phenomena one by one to their simulation, and they found that the atmospheric condition had strong influence on sound propagation. Trunks and canopy scattering became more important at greater distances to the source, but they had not a significant influence on sound pressure levels, when compared to the atmospheric incidence.

In their exhaustive analysis of noise barriers, Kotzen and English [3] state that the best performance of a green barrier occurs at a frequency for which the wavelength is twice the size of the leaves of the trees or shrubs. It makes sense with Aylor's findings [8, 9], more than 30 years earlier. According to [3], green barriers are not expected to control sounds of frequencies lower than 250 Hz, and their best performance is for frequencies of 1000 Hz and higher.

Fan et al. [21] did many measurements behind six dense hedges involving six different evergreen species: arrowwood (*Vibumum odoratissimum*), oleander (*Nerium indicum*), Chinese Photinia (*Photinia serrulata*), bamboo (*Oligostachyum lubricum*), Red Robin Photinia (*Photinia fraseri*), and Deodar Cedar (*Cedrus deodara*). The authors found the best performances for the so-called "leaf shape" (the relation between leaf length to leaf width) between 2 and 3, for the greater leaf area and leaf weight: between 3 and 4 dB/m. Bamboo and oleander did not exhibit good attenuation, but deodar cedar presented very good attenuation at low frequencies (lower than 100 Hz and between 250 Hz and 800 Hz). On the other hand, both *Photinia* species and arrowwood showed their greatest attenuation at frequencies higher than 2000 Hz. Thus, the authors recommend using different kind of species in order to enhance the acoustic behavior of a hedge. They obtained Eq. (6) by regression, and they propose it for calculating the sound attenuation of hedges, in dB/m.

$$\Delta L_{Aep}\ (\mathrm{dB/m}) = 2.705 + 0.266\ W - 3.337\ T - 0.094\ S \tag{6}$$

Where:
W is the leaf weight (g)
T is the tactility; T = leaf weight/leaf area (g/cm^2)
S is leaf shape; S = leaf length/leaf width (m/m)

Horoshenkov et al. [22] demonstrated the importance of the characteristics of leaves for their acoustic performance, especially as sound absorbers. The authors worked with five kinds of plants (*Geranium zonale, Hedera helix, Pieris japonica, Summer Primula vulgaris,* and *Winter P. vulgaris*). The laboratory work was done using an impedance tube (or Kundt tube). The authors also measured the thickness, weight, and area of single leaves, the number of leaves on a plant, the volume occupied by the plant, the dominant angle of leaf orientation, the total area of leaves by plant, the surface density of a single leaf, and the total weight of leaves and stems. The *Winter Primula Vulgaris* had the best acoustic performance, with an absorption coefficient of 0.6 or greater for frequencies between 500 Hz and 1600 Hz. The lowest absorption coefficient was that of *H. helix*, with values lower than 0.2 for all frequencies lower than 1600 Hz.

According to Asdrubali et al. [23], the most important part of the attenuation in a forest is provided by the ground surface. They stated: "*the main absorber is the substrate soil (…). The presence of the plants becomes useful only when a large number of them is installed on the sample, otherwise is even pejorative within some frequency ranges.*"

On the other hand, contemporaneously, Azkorra et al. [24] obtained a weighted sound absorption coefficient of 0.40 with the best absorption behavior at frequencies of 125 and 4000 Hz, and the worst ones at 500 and 1000 Hz.

Li et al. [25] demonstrated that most of the sound absorption by trees is due to its bark properties. The rougher the surface of the bark, better sound absorption performance would be expected. When the bark had moss, the acoustic performance was significantly enhanced. In any case, the absorption coefficients for normal incidence in the range of 160–1600 Hz are actually low: the highest measured values were about 0.1, broadleaved trees having worse results than coniferous trees.

2.3.2 Hoover's expression

According to Palazzuoli and Licitra [26], the attenuation of noise traveling a distance d_f through a dense forest can be estimated using Hoover's expression (Eq. (7)).

$$A_f = \frac{d_f}{100} f^{\frac{1}{3}} \tag{7}$$

Where d_f is the distance through the forest, in meters

f is the frequency, in Hz

2.3.3 ISO 9613-2 approach

The broadly used ISO 9613-2 Standard [5] also considers the attenuation of green barriers as one of the sound attenuation terms, such as geometric divergence A_{div}, atmospheric absorption A_{atm}, ground attenuation A_{gr}, presence of obstacles A_{bar}, and miscellaneous attenuation A_{mis}. One of the miscellaneous attenuation phenomena is just the propagation through foliage A_{fol}. The general equation is Eq. (8).

$$A = A_{div} + A_{atm} + A_{gr} + A_{bar} + A_{mis} \tag{8}$$

The main terms for obtaining the sound attenuation, A_{div}, A_{atm}, and A_{gr}, are presented below. In turn, A_{fol} is also presented.

2.3.4 Acoustic divergence A_{div}

ISO 9613-2 assumes any sound source as a point one. Then, it uses a spherical or quadratic divergence, as presented in Eq. (9).

$$L_{p,r_1} = L_{p,r_0} - 10\ log\left(\frac{r_1^2}{r_0^2}\right) \tag{9}$$

Where:

r_0: distance in meters from the source where its emission sound pressure levels were measured

r_1: distance in meters from the source to the measuring point

$L_{p,r0}$: measured sound pressure level, at a distance r_0 from the source
$L_{p,r1}$: expected sound pressure level, at a distance r_1 from the source

2.3.5 Atmospheric absorption A_{atm}

The atmospheric absorption refers to the attenuation of sound due to traveling through the air along a distance d. According to [5], it should be calculated by applying Eq. (10).

$$A_{atm} = \frac{\alpha \cdot d}{1000} \tag{10}$$

Where:
d: Distance in meters from the source to the receiver
α: Atmospheric absorption coefficient, expressed in dB/km in each octave band.
α depends mostly on the frequency of the sound, the temperature, and the relative humidity of the air. Atmospheric absorption should not be greater than 15 dB at any octave band.

2.3.6 Ground attenuation A_{gr}

The attenuation A_{gr} is mostly the result of the interference between direct and reflected sound waves. This attenuation is mainly determined by the ground surface near the source and receiver. The calculation method proposed in [5] is only applicable if the terrain is flat, either horizontal or with a constant slope.

In order to calculate the attenuation due to ground absorption, three regions are defined (see **Figure 3**).

a. source region: it is the region closer to the source, in the path from the source to the receiver. It covers a length of $30.h_s$, with a maximum distance of d_p. h_s is the source height in meters, and d_p is the distance between source and receiver, in meters.

b. receiver region: it is the region closer to the receiver, in the path from the source to the receiver. It covers a length of $30.h_r$, with a maximum distance of d_p. h_r is the receiver height, in meters.

c. middle region: it is the region between the source region and the receiver region. Its length is $d_p - (30.h_s - 30.h_r)$; it is not defined when $d_p < (30.h_s + 30.h_r)$.

The total ground attenuation is obtained for each octave band, by adding the attenuations occurring in the three abovementioned zones. See Eq. (11)

Figure 3.
Regions to calculate the attenuation due to ground absorption (based on [5]).

$$A_{gr} = A_s + A_m + A_r \tag{11}$$

Where:

A_{gr}: Total sound absorption due to ground effects (dB)

A_s: Sound absorption due to ground effects at the source region (dB)

A_m Sound absorption due to ground effects at the middle region (dB)

A_r: Sound absorption due to ground effects at the receiver region (dB)

ISO Standard 9613-2 [5] explains in detail how to calculate the values of A_s, A_m, and A_r. In the expressions for calculating the attenuation, the acoustic properties of each of these zones are taken into account through the so-called "G factor." When the sound is expected to propagate over hard ground: G = 0; for porous or soft ground: G = 1; and for mixed soil along the sound path, G should take a value between 0 and 1.

2.3.7 Foliage attenuation A_{fol}

ISO 9613-2 [5] states that the foliage of trees and shrubs provides a small amount of attenuation and only if it is sufficiently dense to completely block the view along the propagation path.

According to [5], the attenuation of sound when propagating through a green barrier or dense foliage of thickness d_f, increases with the frequency and with d_f.
The attenuation values are detailed in the Standard for d_f values less or equal to 20 m and greater than 200 m. For thicknesses from 20 m to 200 m, it may be obtained by multiplying d_f by a set of coefficients specified for each frequency band.

3. Case study basic information

As stated, the case study is based on [1]. The main characteristics of the case are presented in Section 1. In this section, it will be presented in detail.

3.1 Sound sources

There are several sound sources at the industrial plant, related to equipment, transportation, and personnel movement. **Figure 4** illustrates the location of the main sound sources at the plant.

The case study is centered only on the emissions from the main noise source in the industrial plant: the coal processing mill. All the measurements selected to work with are representative of this particular situation, since they were specially chosen, and the absence of other operating sources was checked.

The measurements for characterizing the coal processing mill were taken at 12 m distance. **Table 1** presents a representative spectrum of the source emission SPL, in octave bands. It was obtained by composing five SPL measurements, taken on different days. The obtained values were $L_{AF,eq}$ = 83.4 dB and $L_{CF,eq}$ = 84.9 dB.

3.2 Receivers

Two receivers will be considered: P1 and P2, defined as monitoring points on the property line. **Figure 5** shows their location in relation to the plant.

Figure 4.
Main sound sources (drawing overlapped on GoogleEarth image).

f (Hz)	31.5	63	125	250	500	1000	2000	4000	8000
$L_{ZF,12m}$ (dB)	74.5	79.6	72.6	73.1	76.3	78.0	78.3	74.9	64.8

Table 1.
Sound emission spectrum of the coal processing mill at 12 m distance.

3.2.1 Point P1

Point P1 is located facing southwest of the plant, 813 m from the coal mill. Since it is close to a neighboring house, which is temporarily occupied, it is a very important surveillance point. Our study focuses on the results at this point to assess the acoustic behavior of the green barrier.

The background noise at P1 was determined during the shutdown period of the plant. It resulted in a L_{AFeq} value of 40 dB. Its spectrum is shown in **Table 2**.

Table 3 presents the measured SPL at P1 when the coal processing mill was the only noise source operating at the plant. The measured SPL were $L_{AF,eq}$ = 47.7 dB and $L_{CF,eq}$ = 54.0 dB.

3.2.2 Point P2

Point P2 is located on the perimeter of the industrial property, with no nearby houses and close to a large external afforestation. It is located facing southeast, 239 m

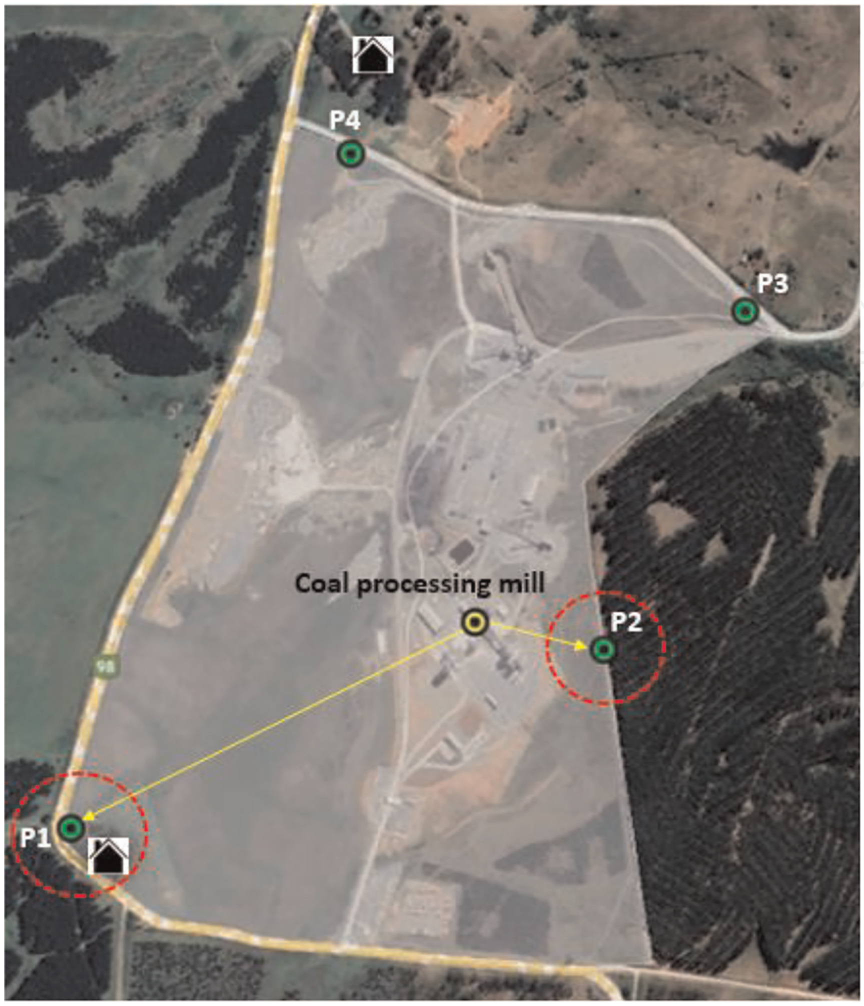

Figure 5.
Relative location of the coal processing mill, P1 and P2 (drawing overlapped on GoogleEarth image).

f (Hz)	31.5	63	125	250	500	1000	2000	4000	8000
$L_{ZF,eq}$ (dB)	50.7	49.4	41.7	35.0	35.4	34.9	30.9	32.0	24.0

Table 2.
Background noise spectrum at P1.

f (Hz)	63	125	250	500	1000	2000	4000	8000
$L_{ZF,eq}$ (dB)	52.1	43.5	45.2	45.4	40.5	40.8	38.3	30.9

Table 3.
SPL spectrum measured at P1 when the coal processing mill was the only operating noise source in the plant.

from the source. Since there are no obstacles between P2 and the coal processing mill, it is the best point to verify the sound depletion law from the source.

The background noise at P2 was also determined during the shutdown period of the plant. L_{AFeq} was 50 dB. The spectrum of background noise at P2 is shown in **Table 4**.

f (Hz)	31.5	63	125	250	500	1000	2000	4000	8000
$L_{ZF,eq}$ (dB)	56.7	59.3	49.0	44.4	45.0	44.6	43.7	39.1	28.0

Table 4.
Background noise spectrum at P2.

f (Hz)	63	125	250	500	1000	2000	4000	8000
$L_{ZF,eq}$ (dB)	67.1	58.2	59.2	60.7	57.3	55.1	49.6	37.3

Table 5.
SPL spectrum measured at P2 when the coal processing mill was the only operating noise source in the plant.

Table 5 presents the measured SPL at P2 when the coal processing mill was the only noise source operating at the plant. The measured SPL were $L_{AF,eq}$ = 62.5 dB and $L_{CF,eq}$ = 68.9 dB.

3.3 Green barrier

3.3.1 Description

The green barrier under study is *Eucalyptus dunii*, with a width of 61 m and a length of approximately 239 m, covering a total area of 1.46 × 104 m^2. It is placed between the coal processing mill and Point P1, 278 m from the mill (see **Figure 6**).

E. dunii is a tree with straight trunk, with dense and drooping foliage. The projected planting technique was staggered diagonally, which is the technique commonly used from the agronomic point of view for planting such species of trees. It is based on the formation of an equilateral triangle between trees. In this case, a variant was made in such a way that the distance between trees in each row was 2.0 m and the distance between rows was 4.0 m. In any case, it can be considered that it is a regular planting pattern, as shown in **Figure 7**. Based on this configuration, there is a surface density of 0.3125 trees/m^2.

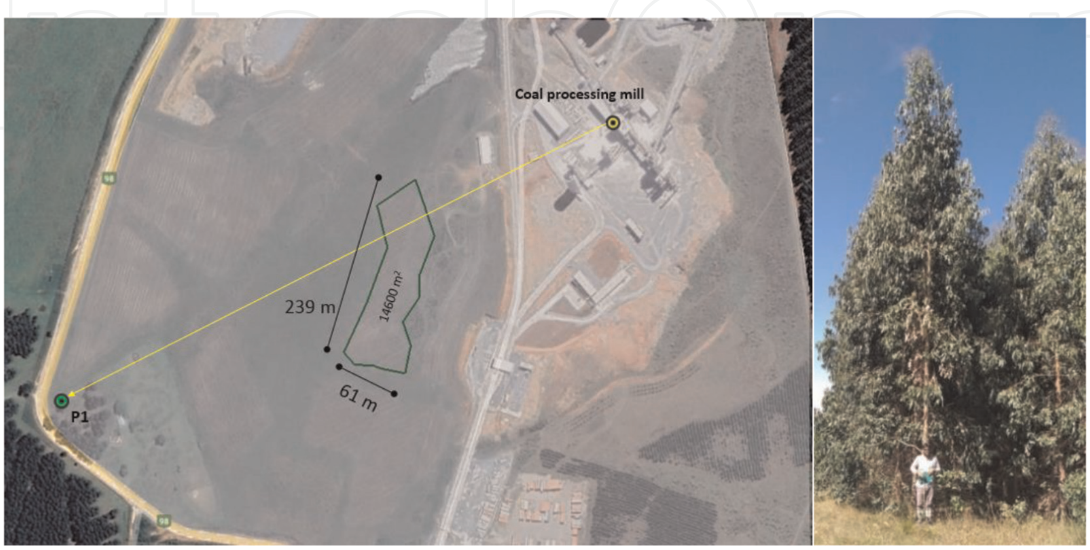

Figure 6.
Location of the tree barrier.

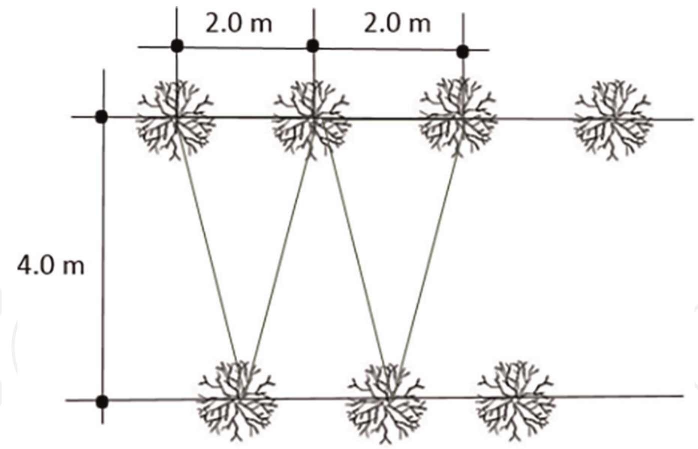

Figure 7.
Staggered planting pattern.

The height of the tree barrier was measured, and the following results were obtained:

- Shortest trees: 8 m
- Tallest trees: 11.3 m
- Average height of the barrier: 10.4 m
- Perimeter of the trunk at shoulder height: 61 cm
- Average length of the leaves: 22 cm

Since the plantation was not created for commercial use, no pruning of root sprouts was done. This practice increases the density of the barrier.

General recommendations	Tree barrier situation
Green barriers are not suitable for controlling low frequency noise [13]	The measured sound pressure levels show that C-A is approximately 2 dB. Thus, the mill sound emissions have no significant low frequency components.
The evergreen trees/shrubs have better acoustic performance than the deciduous ones [16]	It is evergreen eucalyptus. Since they are not for forest use, they are not pruned.
Every 10 m in depth (dense vegetation), approximately 1 dB reduction is achieved [15]	The tree barrier is 61 m thick in the line that joins the source and the receiver. In-depth attenuation of about 6 dB is possible.
The barrier will be more effective when closer to the source [15]	The tree barrier is 278 m from the source and 474 m from the point of measurement.

Low-frequency noise has significant acoustic energy in the frequency range from 20 Hz to 100 Hz. The comparison of the sound level on scale C with the sound level A, allows determining whether or not there are significant low-frequency components. Indeed, since curve A attenuates low frequencies and curve C does not, if the difference between dBA and dBC values is not huge (C-A ≤ 10), it will be considered that the low frequency components are not important [27].

Table 6.
Tree barrier initial check.

3.3.2 Initial check

At first, some general conditions were checked to know if the tree plantation would have a noticeable acoustic performance (**Table 6**).

The tree barrier features make possible to expect some sound pressure levels reduction at P1.

4. Methodology

This study is based on postgraduate research by Cobo Dorado [1]. A large set of SPL measurements were performed, using a CESVA SC-30 Sound Level Meter with Octave Band Analyzer, Type 1 according to IEC 60651:01 and 60,804:00. Calibration was checked before and after each measurement with a portable calibrator CESVA CB006, Type 1. A windscreen was used in all cases. The instrument was placed on a tripod at a height of 1.50 m.

The meteorological variables were measured at each measurement point using a portable climatic station with a digital anemometer Speedtech WindMate 300. A fixed meteorological station located at the perimeter of the industrial plant was used as a local reference element. This station records every 10 minutes, date, time, wind speed (m/s), wind direction (degrees), temperature (°C), and relative humidity (%) and air quality parameters.

A Garmin GPS was used for georeferencing of each measurement point.

To carry out the assessment of the acoustic performance of the tree barrier under study, the following approach has been used:

1. Based on the SPL measured values in the source and the receiver P2, the behavior of the source was analyzed to find the depletion law of sound pressure levels. The objective was determining if the geometric divergence law of the coal processing mill fitted a spherical or a cylindric depletion law.

2. The expected sound pressure levels caused by the coal processing mill at P1 were calculated, only considering the geometric divergence law obtained in the previous step, the atmospheric absorption and the ground attenuation, i.e., the direct propagation without considering the presence of the vegetation barrier.

3. Results were compared with those measured in P1, focusing on the possibility of an extra attenuation due to the presence of the green barrier.

4. The expected SPL from the coal mill at P1 were calculated again, adding the attenuation of the green barrier to the sound pressure levels calculated above. Four different equations were used to estimate the barrier attenuation. When IL equations for solid barriers were used, the diffractions above and along the sides of the barrier were also considered.

5. Results were compared again with those measured in P1.

6. Conclusions about the acoustic performance of the tree barrier and which are the better equations to predict it were found.

All the data processing was performed using electronic spreadsheets.

5. Acoustic performance of the green barrier

5.1 Finding the depletion law of the noise source

The source's emission spectrum measured at 12 m was propagated to obtain the expected spectrum at P2, considering A_{div} and A_{atm}. For calculating A_{div}, both spherical and cylindrical propagations were tested, i.e., applying Eqs. (9) and (12), respectively [1].

$$L_{p,r_1} = L_{p,r_0} - 10\ log\left(\frac{r_1}{r_0}\right) \tag{12}$$

Where

r_0: distance from the source where emission sound pressure levels were measured (12 m)

r_1: distance from the source to P2 (239 m)

$L_{p,r0}$: measured sound pressure level, at a distance r_0 from the source (see **Table 1**)

$L_{p,r1}$: expected sound pressure level, at a distance r_1 (in this case, at P2)

Since the distance from the source to P2 is further than 100 m, the atmospheric absorption will also be considered for this comparison. The atmospheric absorption refers to the attenuation of sound due to traveling along a distance *d*. According to [5], it should be calculated by applying Eq. (10).

In this case, the average temperature and humidity conditions at P2 during the sound pressure level measurements (**Table 5**) were T = 25°C and RH = 50%. The values of α in **Table 7** were taken from Miyara [28].

The results are shown in **Table 8** and **Figure 8**. As it can be seen in **Figure 8**, the linear approach fits better the measured values up to 500 Hz. Thus, the calculation method was not that of ISO 9613-2 [5] because the divergence calculation law was assumed to be not quadratic but linear. All the other attenuation terms were calculated according to ISO 9613-2.

5.2 Sound pressure levels at P1, excluding the tree barrier acoustic performance

SPL at P1 were calculated by using Eq. (12). In this case, r_0 was 12 m and r_1 was 813 m.

f (Hz)	63	125	250	500	1000	2000	4000	8000
α (dB/100 m)	—	0.04	0.13	0.35	0.70	1.18	2.52	7.59

Table 7.
Atmospheric absorption coefficients by octave bands for T = 25°C and HR = 50% (from [28]).

f (Hz)	63	125	250	500	1000	2000	4000	8000	$L_{AF,eq}$
L_{ZF} measured	67.1	58.2	59.2	60.7	57.3	55.1	49.6	37.3	62.5
L_{ZF} calculated with Eq. (9) (quadratic divergence)	53.6	46.5	46.8	49.5	50.4	49.5	42.9	23.8	54.8
L_{ZF} calculated with Eq. (12) (linear divergence)	66.6	59.5	59.8	62.5	63.3	62.5	55.9	36.8	67.8

Table 8.
Comparison of sound pressure levels at P2 using two different depletion laws (all values are in dB).

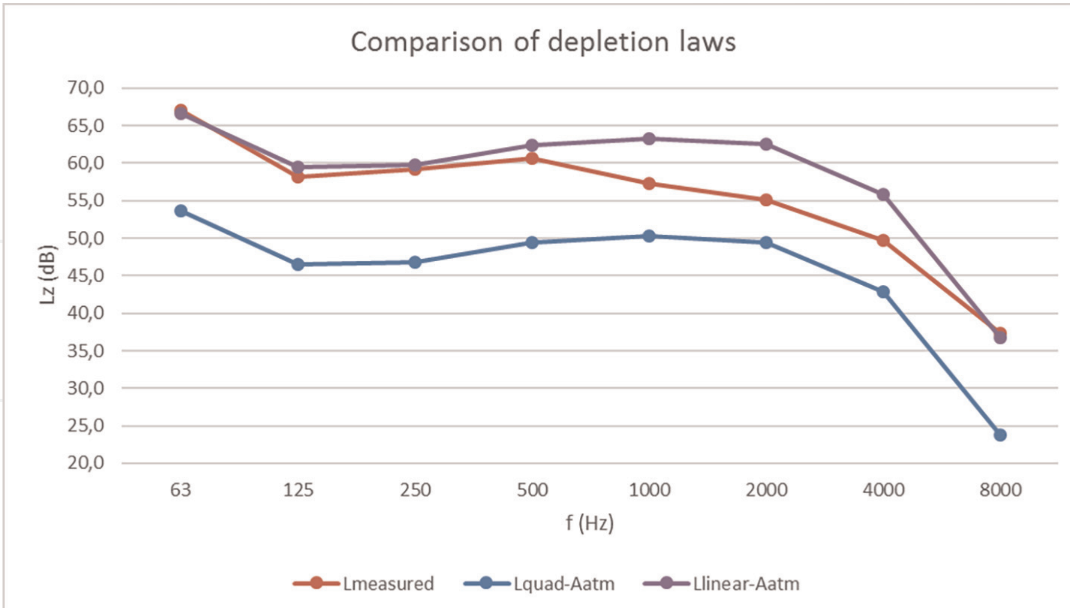

Figure 8.
Comparison of spectra obtained with linear and quadratic depletion laws and the measured spectrum.

Atmospheric and ground absorptions were also considered. Since the ground slope between the coal processing mill and Point P1 is rather uniform (**Figure 9**), the calculation approach proposed by ISO 9613-2 [5] for A_{gr} can be used.

The SPL at P1 were measured when the coal mill was the only noise source operating in the plant. Meteorological conditions during the measurements were considered in selecting atmospheric absorption coefficients (T = 20°C and RH = 80%) (see **Table 9**).

The sound path between the mill and P1 consists of various types of soil, as sketched in **Figure 10**. The length and type of surface of each one are summarized in **Table 10**. The detailed method for calculating G can be found at [5].

Taking into account the height of the source h_s = 3.6 m and the height of the receiver in P1 h_r = 1.5 m, the values of G for each region in **Figure 3** are presented in **Table 11**.

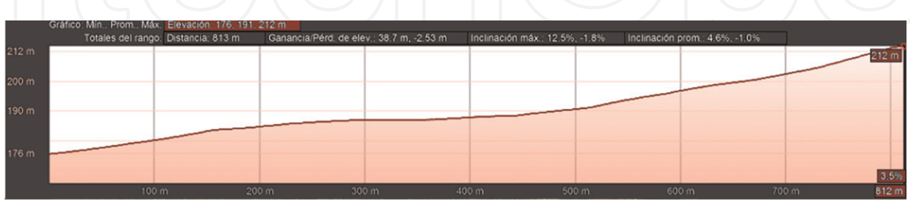

Figure 9.
Diagram of the terrain profile from the coal processing mill to P1 (obtained from Google Earth).

	63	125	250	500	1000	2000	4000	8000
α (dB/100 m)	—	0.03	0.10	0.28	0.52	0.90	2.13	6.86

Table 9.
Atmospheric absorption coefficients by octave bands for T = 20°C and HR = 80% (from [28]).

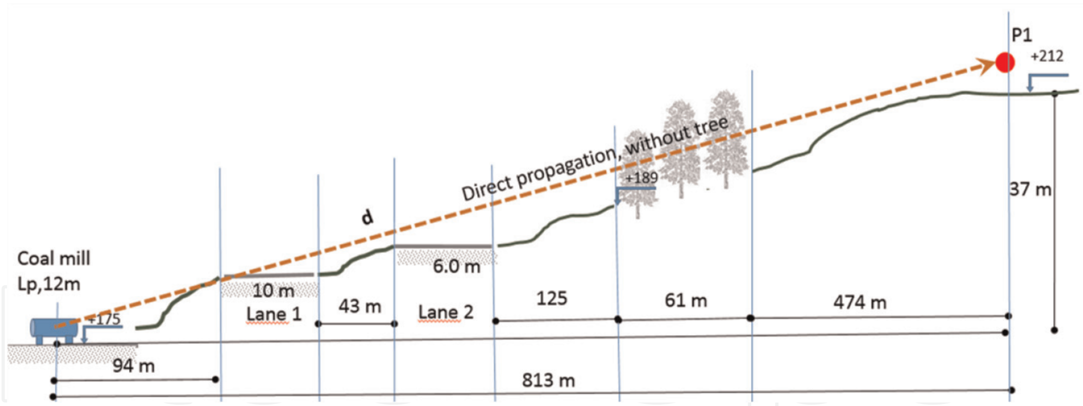

Figure 10.
Diagram of the case study (not in scale).

From	to	Distance (m)	Soil type
Coal mill	End of the mill base	5	Concrete
End of the mill base	Road lane 1	89	Compacted soil
Lower edge of road lane 1	Upper edge of road lane 1	10	Hard pavement
Upper edge of road lane 1	Lower edge of road lane 2	43	Soil
Lower edge of road lane 2	Upper edge of road lane 2	6	Hard pavement
Upper edge of road lane 2	Lower edge of green barrier	125	Soil/Grass
Lower edge of green barrier	Upper edge of green barrier	61	*Eucalyptus dunii*
Upper edge of green barrier	Point P1	474	Soil/Grass

Table 10.
Ground absorption characteristics.

	Source region	Intermediate region	Receiver region
Length	108 m	660 m	45 m
Ground coverage	Concrete/compacted soil/hard pavement/soil	Soil/grass/trees/hard pavement	Soil/grass
G factor	$G_s = 0.2$	$G_m = 0.9$	$G_r = 1$

Table 11.
G values and ground coverage, by region.

The propagation from the sound source, only considering attenuation by distance, by atmospheric absorption, and by absorption from the ground, leads to the results in **Table 12** (calculations were done according to [5]). The 31.5 Hz band was not used, because the atmospheric absorption coefficient does not calculate the same way as it does in higher frequencies.

When comparing the results in the first and the last row in **Table 12**, it appears that the measured values are lower than the ones previously calculated, when expressed in A-weighting scale. The difference is greater at the lowest frequency band and at 1000 Hz and 2000 Hz bands.

According to the background discussed in Section 2, these differences reinforce the hypothesis of an extra sound attenuation, possibly provided by the tree barrier.

f (Hz)	63	125	250	500	1000	2000	4000	8000	$L_{A,eq}$
L_z measured	52.1	43.5	45.2	45.4	40.5	40.8	38.3	30.9	47.7
$L_{Z,813m}$ (Eq. 12)	61.3	54.3	54.8	58.0	59.7	60.0	56.6	46.5	
A_{atm}	0.0	0.2	0.9	2.3	4.2	7.3	15.0	15.0	
A_{gr}	−5.4	3.9	6.1	3.5	−0.8	−1.4	−1.4	−1.4	
$L_{Z,direct}$ at P1	66.7	50.1	47.8	52.2	56.3	54.1	43.0	32.9	59.5

Table 12.
Expected results for direct propagation, without considering the tree barrier (all values are in dB).

Tunick [17] states that the trunks, branches, and crowns are the main agents that attenuate sounds from 1000 Hz to 2000 Hz. On the other hand, according to Martínez Sala [18], the attenuation in frequencies lower than 500 Hz is due to the destructive interference of the sound waves when scattered in a belt of trees planted following a periodic pattern.

5.3 SPL at P1, considering the tree barrier insertion loss (IL)

The IL can be calculated using different formulae. Once the direct sound pressure levels L_{dir} have been calculated considering A_{div}, A_{atm} and A_{gr} (see **Table 12**), the sound pressure levels L_{dif} can be also obtained by difference, using Eq. (1). It is assumed that the SPL at the receiver were only caused by the sound wave diffracted by the barrier, i.e., no direct sound from the source was expected to arrive to P1. It also must be taken into account that there is diffraction by the lateral edges, which must be calculated and added to the previously calculated SPL at the receiver.

In this case study, IL will be calculated according to different methods, to compare their results. The approaches to be considered are: Kurze-Anderson and thick barrier approach, which are general expressions for solid barriers; and A_{fol} from ISO 9613-2 and Hoover's expression, which are specific approaches for green barriers [1, 2, 5, 26].

5.3.1 Kurze-Anderson approach

This way of obtaining IL is a general one; it has not been developed for green barriers. It is expected to overestimate the value of IL.

For a thick barrier, the value of t (**Figure 2**) must be added to the minimum of a and b. In this case, since $b > a$, then $a' = a + t$.

Thus, a = 278.08 m; b = 474.08 m; t = 61 m; a' = 339.08 m; d = 813.00 m.

The IL calculated using Eq. (5) and the SPL expected at the receiver are presented in **Table 13**. Note that the IL for the band of 63 Hz has been considered because the wavelength at this frequency is significantly shorter than the barrier width t.

The calculated SPL at 4000 Hz and 8000 Hz were lower than the background noise at P1; thus, they have been replaced by the background values in **Table 2** (figures in green in **Table 13**).

5.3.2 Thick barrier approach

The verification for this case study (t = 61 m) is presented in **Table 14**.

f (Hz)	63	125	250	500	1000	2000	4000	8000	$L_{A,eq}$
L measured	52.1	43.5	45.2	45.4	40.5	40.8	38.3	30.9	47.7
L_{dir} without tree barrier	66.7	50.1	47.8	52.2	56.3	54.1	43.0	32.9	59.5
IL K-A (Eq. (5))	6.0	6.9	8.3	10.3	12.9	15.8	18.8	21.8	
Expected SPL at P1 (L_{dif})	60.7	43.2	39.6	41.9	43.4	38.3	32	24	46.5

Table 13.
IL according to Kurze-Anderson and expected sound pressure levels at P1 (all values are in dB).

f (Hz)	31.5	63	125	250	500	1000	2000	4000	8000
λ (m)	10.92	5.46	2.75	1.38	0.69	0.34	0.17	0.09	0.04
1/5 t (m)	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2

Table 14.
Verification of thick/thin barrier criteria (all values are in m).

Based on these results, the green barrier could be considered a thick barrier for all the frequencies. Eq. (3) can be used for solid barriers either thin or thick. Since it is not developed for tree or green barriers, overestimation of IL is expected.

The IL calculated using Eq. (3) without subtracting A_{gr} and the SPL expected at the receiver are presented in **Table 15**. Since the distance between the source and P1 is greater than 300 m, K = 1. A_{gr} has just been considered by the general attenuation terms; it must not be subtracted twice.

Note that the IL for the band of 63 Hz has been considered because the wavelength at this frequency is significantly shorter than the barrier width t.

The calculated SPL at 4000 Hz and 8000 Hz were lower than the background noise at P1; thus, they have been replaced by the background values in **Table 2** (figures in green in **Table 15**).

5.3.3 Hoover's expression

Hoover's expression has been presented in section 2, Eq. (7). It depends on the thickness of the green barrier and the frequency of sound.

The IL calculated using Eq. (7) and the SPL expected at the receiver are presented in **Table 16**. In this case, as the main considered phenomenon is the attenuation by the leaves and canopy, attenuation at 63 Hz would not be considered [3].

f (Hz)	63	125	250	500	1000	2000	4000	8000	$L_{A,eq}$
L measured	52.1	43.5	45.2	45.4	40.5	40.8	38.3	30.9	47.7
L_{direct} without tree barrier	66.7	50.1	47.8	52.2	56.3	54.1	43.0	32.9	59.5
IL TB (Eq. (3)) without A_{gr} term	5.6	6.2	7.3	8.9	11.0	13.4	16.1	19.0	
Expected SPL at P1 (L_{dif})	61.1	43.9	40.5	43.3	45.3	40.7	32	24	48.3

Table 15.
IL according to thick barrier approach and expected sound pressure levels at P1 (all values are in dB).

f (Hz)	63	125	250	500	1000	2000	4000	8000	$L_{A,eq}$
L measured	52.1	43.5	45.2	45.4	40.5	40.8	38.3	30.9	47.7
L_{direct} without tree barrier	66.7	50.1	47.8	52.2	56.3	54.1	43.0	32.9	59.5
IL H (Eq. (7))	0.0	3.1	3.8	4.8	6.1	7.7	9.7	12.2	
Expected SPL at P1	66.7	47.0	44.0	47.4	50.2	46.4	33.3	24	53.2

Table 16.
IL according to Hoover's expression and expected sound pressure levels at P1 (all values are in dB).

The only correction needed was that of background noise at 8000 Hz, in order to avoid a calculated value lower than the measured one.

5.3.4 A_{fol} from ISO 9613-2 approach

For this case study, d_f = 61 m. Thus, according to ISO 9613-2, the attenuation values to be considered are presented in **Table 17**.

The IL due to the propagation through a green barrier or dense foliage according to ISO 9613-2 and the SPL expected at the receiver are presented in **Table 18**. No values were needed to be replaced.

5.4 Edge diffraction

When an acoustic barrier is calculated as a "conventional" one (e.g., by using Kurze-Anderson's approach or thick barrier approach), not only the top edge diffraction is to be considered, but also the diffraction at its sides. The SPL due to the diffraction at its sides should be added to the expected sound pressure levels at the receiver.

Figure 11 shows a diagram of the sides that should be considered to obtain the diffracted SPL at the receiver. Since lateral paths are not symmetric, each of them will be calculated separately.

f (Hz)	63	125	250	500	1000	2000	4000	8000
A_f for 20 m ≤ d_f ≤ 200 m	0.02	0.03	0.04	0.05	0.06	0.08	0.09	0.12

Table 17.
Green barrier attenuation, in dB/m (from [5]).

f (Hz)	63	125	250	500	1000	2000	4000	8000	$L_{A,eq}$
L measured	52.1	43.5	45.2	45.4	40.5	40.8	38.3	30.9	47.7
L_{dir} without tree barrier	66.7	50.1	47.8	52.2	56.3	54.1	43.0	32.9	59.5
IL ISO	1.2	1.8	2.4	3.1	3.7	4.9	5.5	7.3	
Expected SPL at P1 (L_{dif})	65.5	48.3	45.4	49.1	52.6	49.2	37.5	25.6	55.5

Table 18.
IL according to ISO 9613-2 and expected sound pressure levels at P1 (all values are in dB).

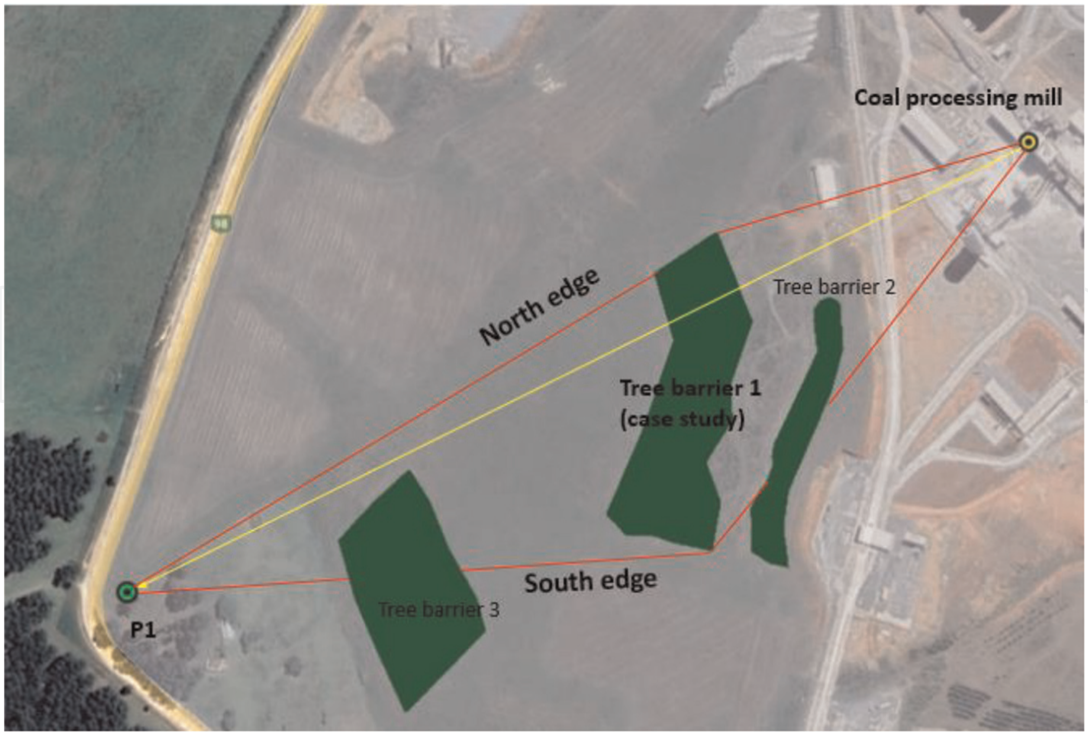

Figure 11.
Diffraction lateral paths to be considered.

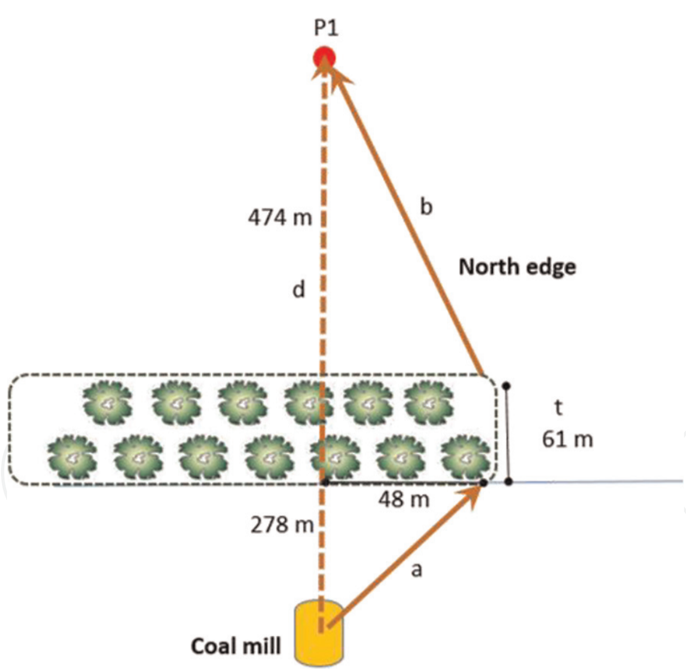

Figure 12.
Diagram of dimensions for calculation of North side diffraction.

5.4.1 North side diffraction

Figure 12 presents the diagram to be used for calculating the North side diffraction. When Kurze-Anderson or the thick barrier approach is used, the calculated sound pressure levels at the receiver were lower than the measured background noise. Thus, they are negligible.

5.4.2 South side diffraction

Figure 11 shows that before the sound reaches the South side of the barrier, it must pass through another plantation of trees along 110 m. After reaching the barrier under study, it has to pass through another forestation, in order to reach the receiver. This complex path may impose greater attenuation than a single tree barrier. Even if there are no simplified methods for calculating the SPL at the receiver in this case, the low SPL obtained at the North side allows to expect negligible results at the receiver.

5.5 Comparison of the results achieved by different calculation methods

Figure 13 shows the SPL in octave bands obtained for different situations and calculation methods.

The blue lines represent the SPL measured at P1: the bottom dotted line corresponds to the background SPL, and the solid one represents the SPL measured when the coal processing mill was the only operating source at the industrial plant.

The upper dotted line represents the calculated SPL without considering the tree barrier (L_{dir}).

All the other lines correspond to different calculation approaches. The green ones were obtained by calculation with methods that consider green barriers (Hoover's and A_{fol} from ISO 9613-2); the red and orange ones correspond to the calculation methods for solid barriers.

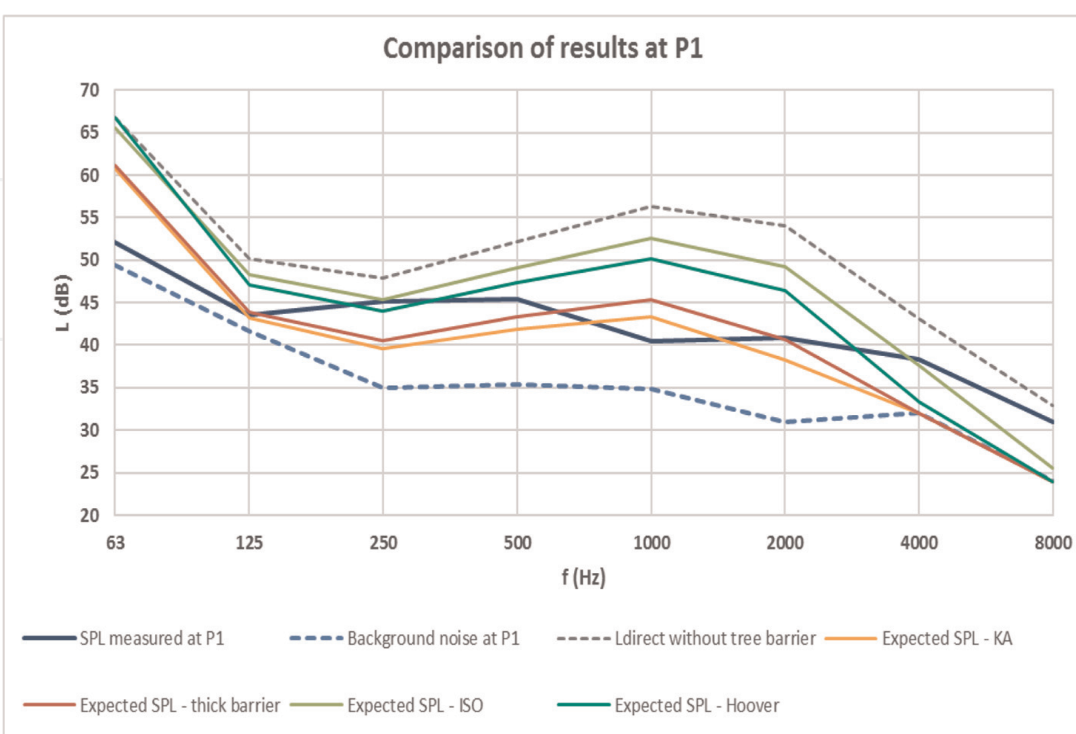

Figure 13.
Comparison of results at P1.

6. Results and discussion

The values of SPL at P2 obtained by measurement and by propagation from the source with two different depletion laws showed that the best fitting was obtained when considering a linear depletion. We focused our comparison on frequencies up to 500 Hz, because at upper frequencies the differences could be related to other phenomena.

When using an approach similar to ISO 9613-2 to propagate the SPL from the source to P1 without considering the eucalyptus plantation, a 12 dB difference was found. This difference could be due to the presence of the trees, which could behave as an acoustic barrier. The greatest extra attenuation was obtained at the frequencies of 1000 Hz and 2000 Hz; according to Tunick [17], this is the frequency range where the trunks, branches, and crowns have their best acoustic performance. Some extra attenuation was also found below 500 Hz; according to Martínez-Sala [18], the differences in this range would be attributed to the destructive interference of the sound waves when scattered in a belt of trees planted following a periodic pattern.

For answering the question about which are the best equations to predict the behavior of the vegetal barrier, the following results are discussed.

The best performance was expected for those formulae developed for green barriers, as Hoover's or the ISO 9613-2 correction term for green barriers. But when calculations were done, they achieved the worst results, being ISO 9613-2 worse than Hoover's (see **Figure 13**).

Just the opposite, the best result for the green barrier IL was achieved in the thick barrier approach, and the second in accuracy was the Kurze-Anderson approach.

In both cases, when adding the edge diffraction, the results did not exhibit any changes, i.e., the edge diffraction was significantly lower than the upper one.

It is noticeable that the results at the frequencies where green barriers are expected to have better performance (1000 Hz and 2000 Hz, according to [3] and [17]) are particularly accurate in both cases. Since these methods have not been developed for green barriers, we did not expect these results.

In order to explain these results, we think that it is possible that the sound waves could behave as if the barrier was a solid obstacle, regarding the long distance between the source and the receiver. Since our atmospheric measurement conditions according to Pasquill-Gifford (see, e.g., [29]) were unstable or neutral atmosphere (wind velocities lower than 5 m/s, variable insolation conditions), this interpretation could oppose [20], by assigning no importance to atmospheric stability conditions.

7. Final remarks

A case study about the acoustic performance of a tree barrier of *Eucaliptus dunii* has been presented. Some different approaches were used in order to calculate its insertion loss *IL*.

The noise source shows a linear SPL depletion law.

Also, the green barrier is performing as an acoustic one.

When comparing the data measured in P1 and the values calculated with direct propagation but without considering the presence of trees, an extra attenuation of approximately 12 dB with A-weighting appeared. The differences in frequencies of 1000 Hz and 2000 Hz wer even greater: 15 dB and 13 dB, respectively. For frequencies of 500 Hz and lower, there are also differences but not as huge as the abovementioned ones. Since this sound attenuation could be intended as due to the presence of the tree barrier, it confirms the hypothesis that green barriers can behave as acoustic ones.

Four options were tried for calculating the sound attenuation provided by the green barrier. Kurze-Anderson and the thick barrier approach gave a good prediction of SPL at the receiver, both in octave bands and for A-weighted values, especially for frequencies between 1000 Hz and 4000 Hz, where the results without considering the tree barrier attenuation were the least accurate. Adding the lateral diffraction did not improve the calculated results in this case.

The best approach for calculating the green barrier *IL* was the thick barrier approach and the second in accuracy was Kurze-Anderson.

The approach of ISO 9613:2 was the least accurate, worse than Hoover's approach.

It is possible that the long distance between the source and the receiver—and also the long distance between the source and the green barrier, makes the barrier behave as if it was a solid obstacle, while the leaves and canopy effects become negligible.

This finding opens the possibility of successfully using the IL prediction equations for solid acoustic barriers (both thin and thick) to estimate the acoustic performance of green barriers, at least under conditions similar to those of this case study. Further research should be needed to recommend wider use, e.g., for distances further than a given one.

Author details

Martha Cobo Dorado, Gissell Rodríguez Milan and Alice Elizabeth González*
University of the Republic, UdelaR (Universidad de la República), Montevideo, Uruguay

*Address all correspondence to: elizabet@fing.edu.uy

IntechOpen

© 2022 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

References

[1] Dorado C, María M. Influencia de la vegetación en la mitigación del ruido. Estudio de una forestación. Universidad de la República, Uruguay: Magister Thesis on Environmental Engineering; 2022

[2] González AE. Overview of noise control techniques and methods. In: Caniato M, editor. Noise Control. London, UK, UK: IntechOpen; 2022

[3] Kotzen B, English C. Environmental Noise Barriers: A Guide to Their Acoustic and Visual Design. 2nd ed. Canadá, USA: Simoultaneouly Published; 2009

[4] Menounou P. A correction to Maekawa's curve for the insertion loss behind barriers. The Journal of the Acoustical Society of America. 2001, 2001;**110**:1828-1838

[5] International Standard Organization. ISO 9613- Acoustics — Attenuation of sound during propagation outdoors — Part 2: General method of calculation. 1996

[6] Eyring CF. Jungle acoustics. The Journal of the Acoustical Society of America. 1946;**18**(2):257-270

[7] Embleton T. Sound propagation in homogeneous deciduous and Evergreen woods. The Journal of the Acoustical Society of America;**35**:1119-1125

[8] Aylor D. Sound transmission through vegetation in relation to leaf area density, leaf width, and Breadth of Canopy. The Journal of the Acoustical Society of America. 1972;**51**:411-414

[9] Aylor D. Noise reduction by vegetation and ground. The Journal of the Acoustical Society of America. 1972, 1972;**51**:197-205

[10] Johansson E. The Sound Amplifyng Forest, with Emphasis on Sounds from Wind Turbines. Göteborg, Sweden: Chalmers University of Technology; 2010

[11] Price Margaret A, Attenborough K, Heap Nicholas W. Sound attenuation through trees: Measurements and models. The Journal of the Acoustical Society of America. 1988;**84**:1836-1844

[12] Lee SE, Velasquez S, Flintsch G, Peterson J. Road Noise Attenuation Study: Traffic Noise, Trees, and Quiet Pavement: A Report in Response to item 442 c. of Chapter 847 of the Acts of Assembly of 2007. USA: The Virginia Transportation Research Council; 2008

[13] Huddart L. The Use of Vegetation for Traffic Noise Screening. United Kingdom; 1990

[14] Huisman WHT, Attenborough K. Reverberation and attenuation in a pine forest. The Journal of the Acoustical Society of America. 1991;**90**:2664

[15] Ochoa de la Torre. La vegetación como instrumento para el control microclimático en línea. Tesis Doctoral. Universidad Politécnica de Cataluña consultado en agosto de 2022

[16] Tarrero AI.. Propagación del sonido en bosques. Análisis comparativo de las medidas in situ, en laboratorio y de los valores predichos por un modelo en línea. Tesis Doctoral. Universidad de Valladolid consultado en agosto de 2022. 2002. https://www.cervantesvirtual.com/obra/propagacion-del-sonido-en-bosques-analisis-comparativo-de-las-medidas-in-situ-en-laboratorio-y-de-los-valores-predichos-por-un-modelo–0/

[17] Tunick A. Coupling Meteorology to Acoustics in Forests. Adelphi, MD: U.S. Army Research Laboratory; 2002

[18] Martínez-Sala R, Rubio C, Sánchez Pérez EA, Linares J. Control of noise by trees arranged like sonic crystals. Journal of Sound and Vibration. 2006;**291**:100

[19] Onuu MU. Modelling of excess noise attenuation by grass and forest. Nigerian Journal of Physics. 2006;**18**:197-202

[20] Swearingen ME, White MJ. Influence of scattering, atmospheric refraction, and ground effect on sound propagation through a pine forest. The Journal of the Acoustical Society of America. 2007;**122**:113

[21] Yang F, Bao Z, Zhu Z, Jiani L. The investigation of noise attenuation by plants and the corresponding noise-reducing spectrum. Journal of Environmental Health. 2010;**72**:8

[22] Horoshenkov Kirill V, Khan A, Benkreira H. Acoustic properties of low growing plants. The Journal of the Acoustical Society of America. 2013;**133**: 2554

[23] Asdrubali F, D'Alessandro F, Mencarelli N, Horoshenkov KV. Sound absorption properties of tropical plants for indoor applications. In: The 21st International Congress on Sound and Vibration. Beijing/China; 2014

[24] Azkorra Z, Pérez G, Coma J, Cabeza LF, Bures S, Álvaro JE, et al. Evaluation of green walls as a passive acoustic insulation system for buildings. Applied Acoustics. 2015;**89**:46-56

[25] Li M, Renterghem V, Timothy, Kang J, Verheyen K, Botteldooren D. Sound absorption by tree bark. Applied Acoustics. 2020;**165**:9

[26] Palazzuoli D, Licitra G. Chapter 1 fundamentals. In: Licitra G, editor. Noise Mapping in the EU, Models and Procedures. Boca Raton, USA: CRC Press; 2013. p. 412

[27] Boletín Oficial del Estado Español. Real Decreto 1367/2007, de 19 de octubre, por el que se desarrolla la Ley 37/2003, de 17 de noviembre, del Ruido, en lo referente a zonificación acústica, objetivos de calidad y emisiones acústicas. BOE núm. 254, de 3/10/2007. 2007

[28] Miyara F. Control de ruido. Rosario, Argentina: Own Electronic Edition; 1999

[29] Wark K, Warner CF. Contaminación del aire: origen y control. México: LIMUSA; 1990