FACULTY OF BIOSCIENCE ENGINEERING

# HOW TO DESIGN EFFECTIVE WOODY VEGETATION BELTS FOR NOISE POLLUTION REDUCTION?


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*„Eines Tages wird der Mensch den Lärm ebenso unerbittlich bekämpfen müssen, wie die Cholera und die Pest.“*

“One day people will have to fight noise just as relentlessly as they fight cholera and the plague.”

— Robert Koch
German physician, microbiologist and
Noble Prize Winner (1843-1910)

# Summary

Noise is a problem in Flanders and Western-Europe. Since the EU directive of 2002 on noise pollution and worldwide recognition of the health risks induced by noise exposure, solutions for noise reducing infrastructure are needed.

The idea of using trees or forests for noise mitigation purposes is not new, but the rather unambiguous effects seem to fade the use into the background. One of the significant contributions of noise attenuation by tree belts or forests is the ground effect of forest floors. Despite its large impact, studies seem to focus more on the above ground part of forests. In this study the impact of tree species or litter quality classes on the forest floor is researched. By selecting species or specific acoustical traits, forest floor can be designed to improve the ground attenuation.

A two microphone set-up was explored to find, by reverse engineering, the soil characteristics determining the acoustical behaviour of the forest floor. Reverse engineering, performed with acoustical impedance models found in literature provided the link between data and model parameters. In the Mortagne-forest, acoustical and non-acoustical data was gathered. This data included soil and litter samples and acoustical measurements performed, focusing on the plant litter effect, e.g. measurements with and without litter layer.

Findings included the litter layer effect being clearly visible between species. Acoustic parameters derived from model fitting differed significantly between species/litter quality classes. The removal of the litter layer did seem to affect the measurement significantly. This would suggest that the litter layer is the important factor in sound mitigation. Mainly species with thick litter layers, beech and northern red oak, seem to be optimal for noise attenuation. These species are also cause soil acidification, if desired this could be mitigated with soil enriching species. So, the advise for the design of a tree belt is planting species with a thick litter layer and thereby preferably creating a rich structure.

**Keywords**: Impedance models, tree species, litter layer, traffic, noise, mitigation, Nordtest, ground effect

# Samenvatting


Geluidshinder is een probleem in Vlaanderen en West-Europa. Sinds de EU in 2002 een richtlijn heeft opgesteld en er wereldwijde erkenning is voor de gezondheidsproblemen door geluidshinder, zijn er oplossingen voor geluidswering nodig.

Het idee om bomen of bossen te gebruiken voor geluidsreductie is niet van vandaag. Toch lijkt door het gebrek aan eenduidige resultaten, het gebruik naar de achtergrond verdwenen. Eén van de belangrijkste contributies van geluidsdemping door bossen of bomenrijen is het grondeffect van de bosbodem. Ondanks de relatieve grootte ervan, lijken studies zich voornamelijk te focussen op het bovengrondse deel van bossen. In deze thesis wordt de impact van boomsoorten of strooiselkwaliteitsklassen op de bosbodem onderzocht. Door soorten of bepaalde akoestische eigenschappen te selecteren, kan de bosbodem gecreëerd worden met maximale demping door het grondeffect.

Een opstelling met twee microfoons werd getest om, via *reverse engineering*, de bodemeigenschappen te bepalen die belangrijk zijn voor het akoestisch gedrag van de bosbodem. Voor de *reverse engineering* werden impedantie modellen uit de literatuur gebruikt. In het Mortagnebos werden akoestische en niet-akoestische gegevens verzameld. Deze gegevens omvatten bodem-en strooiselstalen en akoestische metingen, met een focus op het kwantificeren van het strooiseleffect e.g. metingen met en zonder strooisellaag.

Het strooiseleffect tussen de soorten is duidelijk zichtbaar. Akoestische parameters afgeleid van de *model fitting* verschilden statistisch significant tussen soorten/strooiselkwaliteitsklassen. Het verwijderen van de strooisellaag leek daarbij een significante invloed te hebben. Dit zou dus betekenen dat de strooisellaag een invloed heeft op geluidsdemping. Voornamelijk soorten met een dikke strooisellaag, beuk en Amerikaanse eik, leken het best voor geluidsdemping. Maar deze soorten worden ook geassocieerd met bodemverzuring, indien nodig kan dit effect met bodemverbeterende soorten worden verholpen. Het advies voor de beste bomenrij is dus soorten met een dikke strooisellaag op die manier planten dat een rijke structuur gecreëerd wordt.



**Sleutelwoorden**: Impedantie modellen, boomsoorten, strooisellaag, verkeer, lawaai, demping, Nordtest, grondeffect

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# Abbreviations & Symbols

## Abbreviations

| | |
|---|---|
| BNC-connector | Bayonet-Neill-Concelman-connector |
| DALY | Disability-Adjusted Life Years |
| D&B | Delany and Bazley-model |
| EU | European Union |
| FAP | Fixed Area Plot |
| IHD | Ischaemic Heart Disease |
| MIRA | *Milieurapport* |
| NS | Noise Sensitivity |
| NT error | Nordtest error (Equation 3.9) |
| RMS | Root Mean Square |
| RMSE | Root Mean Square Error (Equation 3.8) |
| RPM | Rotations Per Minute |
| SLO | *Schriftelijk Leefomgevingsonderzoek* |
| SNR | Signal-to-Noise Ratio |
| SPL | Sound Pressure Level |
| .wav | Waveform Audio File Format |
| WHO | World Health Organization |
| Z&K | Zwikker and Kosten-model |

## Symbols

| | |
|---|---|
| $\alpha$ | atmospheric absorption coefficient (in dB unit length) |
| $\alpha$ | absorption coefficient of surfaces |
| dB | decibel |
| dB(A) | A-weighted decibel |
| $c_s$ | structure constant |
| $\Delta L$ | sound pressure level difference |
| $f_c$ | center frequency of 1/3-octave or octave band |
| Hz | hertz for frequency |
| k | sound wave number |
| $L$ | layer depth |
| $L_e$ | estimated depth of rigid layer, layer depth estimated by a measurement |
| $L_{den}$ | noise level day-evening-night in dB(A) |
| $L_{night}$ | noise level night in dB(A) |
| $\omega$ | angular frequency |
| $\Omega$ | porosity of a porous medium |
| Pa | pascal |
| $\sigma$ | flow resistivity |
| $\sigma_e$ | effective flow resistivity, flow resistivity derived from a measurement |
| V | volt (usually mV in acoustics) |
| W | average acoustic power |
| $Z_n$ | acoustic impedance at normal incidence |

# 1 | Introduction

## 1.1 Context

Since multiple decades people are aware of the possible risks and adverse health effects due to excessive noise exposure [1–3]. Given the relevance for public health, solutions are needed. But to reach a solution, first the problem has to be characterised.

One of the main sources of environmental noise is transportation noise. It causes sleep disturbance, annoyance and the most lost life years in Western-Europe [4]. The conclusion is that the urge for a solution is there and is increasing. Especially since in 2002 the EU published a noise directive [5], about the maximal degree to which people may be subjected to noise. Therefore countries and cities are looking at different options.

To help and mitigate, this thesis will try to provide an idea on how to attenuate surface transportation noise in the greenest way possible: forests. Forests can provide many ecosystem services while also mitigating the noise problem. They provide services like air pollutant removal, carbon storage, carbon sequestration sequestration, urban heat island reduction, stormwater runoff reduction, look pleasing, house animals and plants. Furthermore, research by Frumkin et al. has been conducted on the sound mitigating capacity [6]. Trees can reduce noise by sound wave interactions with leaves, branches, trunk, bark and also the soil under the tree can have an impact [7]. It is the latter that will be studied in this thesis and more precisely the difference in ground attenuation between species. As an ultimate goal, this paper tries to provide a directive to road managers and helps them making choices.

**Figure 1.1:** Image illustrating the different causes and problems of environmental noise pollution. Urban sound (industry, cities), airplane, train and car traffic are the main causes of noise induced health problems such as psychological problems (brain), fatigue (bags under eyes) and cardiovascular (heart) diseases [8].

## 1.2 Short overview of the structure

The thesis is divided in several parts. First a literature review in which the following subjects will be addressed: the problems induced by noise; the sources of noise; the current situation in Flanders; some of today's solutions in noise mitigation and soil potential for this purpose. To end the literature study, the research goals will be presented.

In the second main section, the used material and methods in this thesis will be discussed. A quick introduction in ground acoustics is given, together with the idea of the measurement set-up and the practical side of the fieldwork. Then the forest is presented where the fieldwork was conducted. Together with an explanation for the sampled non-acoustical soil characteristics.

In a third part, the results are presented in summarizing tables, graphs and are discussed in the subsequent section.

To conclude the thesis some general remarks, thoughts, findings and, finally, some propositions on future research ideas are given.

# 2 | Literature review

## 2.1 Noise pollution and health effects

The noise problem in urban areas is one that cannot be ignored any longer. In many studies it is pointed out as one of the main drivers of environmental related DALY's (Disability-Adjusted Life Years) [1, 9]. DALY's are healthy years lost in comparison to the normal life expectancy, due to ill-health, living with a disability/disease or early death.

The World Health Organisation (WHO) has found out that 15 percent of people would describe themselves as suffering severe annoyance from noise [10]. The auditory system is constantly capturing and processing sound [11], this means that even while sleeping the brain is 'hearing' things. For, long it has been unclear to what extend this impacts people's life. This became more transparent after a lot of research, mainly with questionnaires on peoples perception on certain noise events and the respective annoyance. Thanks to this research, it is now known that noise has a significant impact on problems like sleeping disruption and stress levels. Although solutions are available, the problem lies more in the link between researchers and policymakers, more influence of scientists is needed for good policy decisions.

In the past years, researchers provided enough evidence on adverse health effects specifically induced by noise [1–4, 6, 11–13]. In a medical context, the first thing that comes to mind with noise is hearing damage. This can be loss of hearing, but also tinnitus, defined as a sensation of sound (e.g. roaring, hissing, or ringing) in the absence of an external sound source. These two symptoms are mostly the result of high intensity noise events or too loud environments, e.g. factories, construction sites or parties/festivals [12]. Hearing damage commonly caused by irreversible harm to the cochlear hair cells in the cochlea of the inner ear, the *snail shell like* structure. The underlying mechanism is that loud sound overstimulates delicate hair cells, leading them to be injured or die. Once the damage is done the human auditory system cannot regenerate or be healed [14].

The second, more silent, medical problem of noise usually is caused by elevated levels of stress hormones like cortisol. When the level of these hormones rise, people constantly feel stressed. The body is reacting as if it is in a stress inducing situation (e.g. danger, fear, ...). For a moment this is a normal reaction to noise, but on the long-term it can have severe adverse health effects like depression and, in some cases, cardiovascular problems [13].

Furthermore nocturnal environmental noise can cause sleeping problems. Noise events during the night cause changes in the sleep architecture [15], which in turn cause tiredness, annoyance, entering a downwards spiral in which the same effects as described above are reached [16].

A regional research of WHO in Europe reports that there is now sufficient information available to quantify the burden of disease from environmental noise. Diseases induced by noise include cardiovascular disease, cognitive impairment in children, sleep disturbance, tinnitus and annoyance. The report is based on a limited set of data, several calculations and assumptions. It is estimated that DALY's lost from environmental noise in European union Member States and other Western European countries are equivalent to a total of 61 000 years for ischaemic heart disease (IHD), 45 000 years for cognitive impairment in children, 903 000 years for sleep disturbance, 22 000 years for tinnitus and 587 000 years for annoyance [4]. These results indicate that at least one million healthy years of life are lost every year from traffic-related environmental noise in Western Europe. Because overestimation is usually avoided, these numbers can be considered as *conservative* and realistic.

The different forms of annoyance that occur are diverse and range from mild to very severe. It is clear that people are in general annoyed by the sound of traffic. This is not very surprising given the densely populated area in Western Europe, 180 inhabitants per square kilometre [17]. Until now the existing evidence compromises mainly physical problems. The mental side however, still remains under-researched. Mental non-auditory effects like depression and anxiety are difficult to study. That is why Park et al. researched the noise sensitivity (NS) to explain why people have different grades of annoyance to noise. He found that NS, rather than noise itself, is associated with an elevated grade of susceptibility to non-auditory effects. NS is a stable trait that is independent of increasing noise exposure. It characterises individuals' susceptibility to noise and hence moderates their reactions to it. When comparing a group of individuals exposed to the same noise, those with high NS are more likely to pay attention to the noise, to interpret the noise negatively as a threat or annoyance, and to react emotionally, compared to those with low NS. Consequently, it is difficult for those with high NS to become habituated to noise [19].

It is clear that noise can cause a lot of problems. Therefore the WHO has set a threshold of 55 dB(A) for the $L_{den}$ where people may be exposed to. $L_{den}$, L for sound level in dB(A), dB(A) means that the dB value is A-weighted or corrected for the human ear. The way the human ear perceives loudness is not equal for all frequencies, by correcting the dB-value this problem is addressed. DEN stands for **D**ay-**E**vening-**N**ight. $L_{den}$ is a logarithmic average, see Equation 2.1, of the noise levels during the day (7AM-7PM), evening (7PM-11PM) and night (11PM-7AM). But it is not just the logarithmic average of these three values, the noise levels in the evening and night are penalized with $+5$ dB(A) and $+10$ dB(A), respectively.

$$L_{den} = 10 \cdot {}^{10}\log \frac{12 \cdot 10^{\frac{L_{day}}{10}} + 4 \cdot 10^{\frac{L_{evening}+5}{10}} + 8 \cdot 10^{\frac{L_{night}+10}{10}}}{24} \tag{2.1}$$

This weighing is done because in the evening and night, noise is experienced as more disturbing then during the day. This difference between noise during day and night led to the proposal of a second value by the WHO, $L_{night}$. This value has an even lower threshold at 45 dB(A), because at higher noise levels during the night people don't reach the amount of time in the REM-sleep [15, 20, 21].

## 2.2 Source of noise pollution

The sources of noise pollution are diverse and multifactorial. This thesis focuses solely on noise emitted by surface transport (e.g. cars, motorbikes, trucks, trains). Not addressed is noise from other means of transport, such as airplanes or urban sources, like industry. Annoyance from these sources are only regarded regionally significant. Air plane noise is seen as relevant only at take off and landing, so the problem occurs only close to an airport. For industry a likewise thinking pattern is followed.

The choice for surface transport is in a civilised region like Flanders not peculiar. In the questionnaire *Schriftelijk leefomgevingsonderzoek* (SLO), carried out by by the Flanders Environment Agency, is shown that the biggest source of exposure is coming from traffic and transport (31%) for people who feel moderately to severely annoyed by sound [22].

Traffic noise has, like all sound sources, a specific frequency spectrum. Both depicted graphs in Figure 2.1 are theoretical approximations of the sound pressure level (SPL) in dB(A) for a passage of a car (left) and a heavy truck (right). The interval of the graph is on the lower side of the spectrum and has a maximal value at around 1000 Hz for a car and a bit lower for the truck (600 Hz-1000 Hz). This is a representation of only one passage, the SPL will be higher when there is a lot of traffic. The key idea is that human perception of traffic will mainly be in the frequency spectrum of 125-4000 Hz, with a peak around 1000 Hz [23]. For this figure it needs to be pointed out that no atmospheric refraction

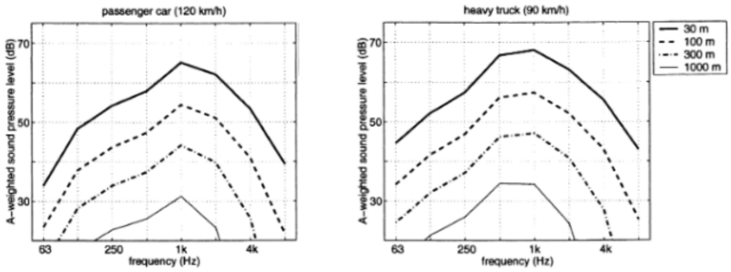



**Figure 2.1:** A-weighted octave band spectra of the SPL of a noise source. The spectra are shown for 4 different distances from the source. The spectra have been calculated at temperature of 10 °C and 80% relative humidity to calculate the $\alpha$ term. On the left: From a car at 120 km/h. On the right: From a heavy truck at 90 km/h [23, 24]

nor ground reflections are implemented in the formula of the model, it is the pure sound emission from measured sound power spectra [24].

## 2.3 Traffic noise pollution in Flanders

In Flanders, due to its high density population and an average of 5.29 km roads km$^{-2}$ [25] noise pollution is a highly topical problem and the numbers are on average worse than for the rest of Western Europe. The results of the *Milieurapport* (MIRA) [9], conducted in 2012, (see Figure 2.2 indicated that with seven percent, noise pollution is the second largest cause of DALY's caused by environmental stressors in Flanders. Although it is roughly only one tenth of the DALY's caused by emissions of fine particles, it still accounts for a significant amount.

Over the years there is also not a lot of improvement, as is seen in Figure 2.3. The previously mentioned periodical questionnaire carried out by the SLO shows that a lot of people are moderately to extremely annoyed by noise [22]. The trend seemed to move downward since 2004 but went back up in 2018, meaning that people are more annoyed or that people now have a higher sensitivity to it [18]. Another reason could be that, because of the financial crisis, there was less traffic on the roads, especially a lower amount of freight transport with heavy trucks [26]. So this could explain the lower values in 2012.

However for a significant number of people not the heavy trucks or highway traffic is the problem but the periodic events in the countryside that cause annoyance/disturbance. This is a problem that is quite significant in Flanders because of the poor urban planning and the continuous investments of municipalities investing in roads, which is 19% of their annual budget [27]. Investment

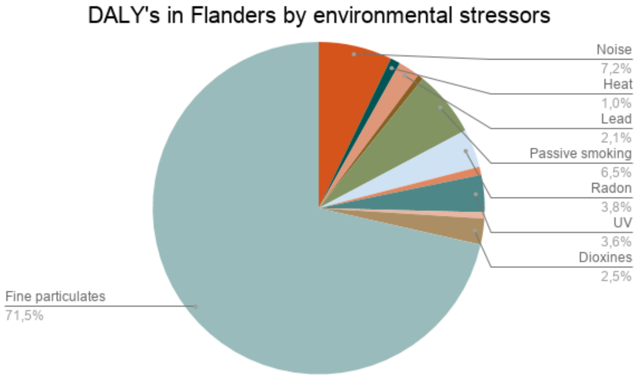



**Figure 2.2:** DALY distribution by environmental stressors for the Flemish region. The sum of DALY's for Flanders is 102 492 years. Data collected from MIRA [9].

in silent roads is also possible, but this is generally still in the research phase in Flanders [28]. The large amount of investments in road infrastructure means that a lot of small roads are built. They cause these peak values that are known to disturb sleep. An indicator like $L_{night}$, noise levels during the night, should be looked at along with the amount of noise events and their sound level [4]. Lastly some interviewees indicated in the SLO that traffic, more than anything else, is the reason of sleep disturbance. It can thus be concluded that Flanders has a noise pollution problem and solutions are desired.

## 2.4 Options for noise mitigation

There are many different options available for the reduction of noise pollution. Most people have probably noticed one or more solutions while driving. The best-known solution is the *classic* noise barrier. For many decades it has been known for its effective reducing capacities at short distance, to up to 10 dB(A) [29]. But they also have downsides, they are not very visually pleasing, costly (€ 1000-1200m$^{-1}$ [30]) and also lose effectiveness at higher wind speeds due to refraction over the screen. In order to combine visually pleasing and effective, the trend of moving to a combination of vegetation and noise barriers is increasing. The multiple benefits they provide will be discussed in the next section.

### 2.4.1 Hybrid solutions

The options for green solutions are manifold. On the one hand there are hybrid green solutions, e.g. a classic noise barrier is overgrown with vegetation. Furthermore there is also a non-biological matrix (steel, bricks, concrete) wherein soil or a substratum is added so plants can establish themselves. Figure 2.4 is

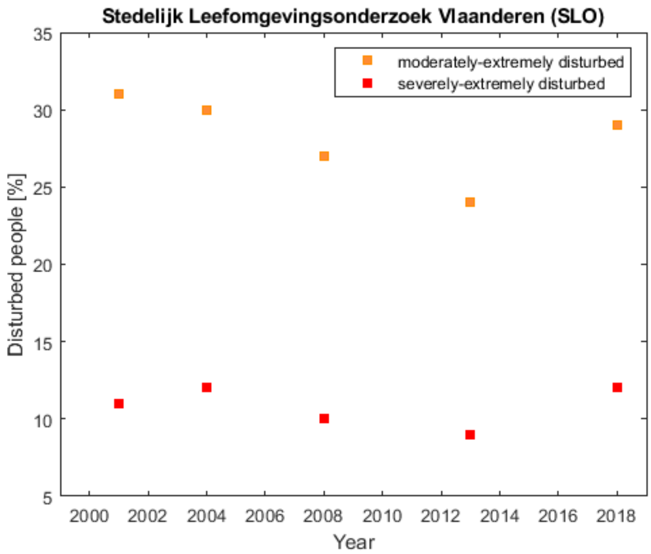



**Figure 2.3:** Results from SLO, a questionnaire done by the Flemish government. Hereby the sample size was on average 5000 participants. On the y-axis it shows the percentage of people who were moderately-extremely (orange) and severely-extremely annoyed (red) by noise [22].

an example designed by a project funded by the EU: Urban Green UP [31]. The project tries to find innovative nature-based solutions for cities of the future. They designed a green noise barrier that is made of a metal frame and a wool substratum where also plants can grow in. In this noise barrier, the type of wool is particularly chosen to favor the absorption of sound. A hybrid barrier like this is a good example of a more aesthetically pleasing solution that is constructed of natural and non-natural elements. Next to the noise mitigating capacity, it is also good for the hydrological cycle in comparison to the classical hard noise barriers.

### 2.4.2 Fully biological solutions

#### Earth mound

On the other hand, there are fully biological solutions like earth mounds, trees, tree belts, rows of bushes and complete forests. The earth mound can be used to reduce sound and will be overgrown with vegetation. For example in Bourgoyen-Ossemeersen Figure 2.4(right), Ghent along the ring around the city. One of the red regions, marked with a white frame, on Figure 2.7. This earth mound generates a good sound reduction over a relatively small amount of distance. Costs in this particular example could be minimized by using excavation material out of the marshes and not having to transport soil over long distances. This

**Figure 2.4:** Two possibilities to approach green solutions for noise mitigation. A bio-barrier, for example of a hybrid form with a metal structure and wool substrate (left) [31]. A fully biological solution, an earth mound as seen in the Bourgoyen, see white frame Figure 2.7. The earth mound's principle is based on the noise absorption by the the physical presence of soil [32].

is thus a more engineered way of using soil as a sound absorber and sometimes combined with a noise barrier on top or trees.

### Trees as noise barrier

The idea of using trees or forests as a noise barrier is not new [33]. During a timespan of almost 50 years, quite a lot of studies have been performed on this topic. Figure 2.5 illustrates the ways a tree can interfere with sound waves. Our interest is mainly the litter or fallen leaves component. Because the other components have a larger influence on the higher frequencies and as seen in Figure 2.1 these are not within the spectrum of interest.

Research conducted on the leaf effect indicated that mainly the higher frequency spectrum (>2-3kHz) get absorbed by leaves [34]. It must be pointed out that this is not the main effect for sound reduction by leaves. The scattering effects will be higher for all frequencies, also the lower frequencies that do not get absorbed. Effects of a longer traveling time through vegetation will thus be considerable and wider vegetation belts make sense.

The bark/stem also has a rather limited effect. A recent study [35] showed an absorption coefficient of roughly 0.05 at frequencies below 1kHz, the frequencies of transportation noise, see Figure 2.1. This absorption effect can thus be regarded as less important. But, scattering of stems is one of the main effects in noise attenuation by trees [7].

When looking at studies of complete trees as noise reducers, the results were never unambiguous. These divided findings are the main reason why the effect of tree belts and forest on sound attenuation along transport corridors is often dismissed [36]. Some concluded that the effect is rather limited [37]. But Kragh has been pointing out a non-auditory advantage delivered by using trees or forests as noise barrier. This advantage was that people perceived less annoyance from noise by seeing green elements and the covering effect by trees of sound sources. This is confirmed in a more recent study by Bangjun, Lili and Guoqing [38]. The annoyance experienced by people will thus be less because of these other, non-acoustical, factors. This psycho-acoustical aspect was also seen by Meloni, lower degrees of annoyance towards noise when seeing naturally constructed noise barriers [39]. This effect is seen only at lower sound pressure levels, at higher SPL the positive effect is from another mechanism. In that SPL range the psycho-restorative effect seems to be dominant, by relieving stress it can compensate for the stress inducing effects of noise [40].

Others concluded that the sound is effectively reduced [41], Huddart found a reduction of 6 dB(A), in a dense spruce forest, in comparison to a same depth 30m (100ft) grassland. Leonard, Parr et al. and Reethof found even more profound effects and reported that a 15-30m thick dense belt of trees and shrubs could lower the noise with 6-10 dB(A) [42, 43] .

Furthermore, relationships are found between the height of trees and the attenuation. Trees do show positively related terms in the first years, up to a height of 10-12 meters. This is not really the height effect but rather the way trees grow in their first years, trees tend to have more branches spread over the stem in the first years, creating more structure and scattering surface. But after canopy closing, due to self pruning, attenuation decreased [44]. As mentioned before, is in general scattering by stems regarded as one of the main mitigating effects by tree belts [7].

Another way to use trees is to combine them with other noise reducing infrastructure like noise barriers. It was found that the effect of trees mainly increased the performance of the noise barrier when evaluated downstream. This because the effect of wind on the propagation of sound is affected by the trees and wind speed gradients. Downwind effects up to 4 dB(A) were found [45]. In the case of upwind, the effect was rather limited.

## 2.5 Forest soil as green noise mitigation solution?

It has been long known that soil effects can be significant on sound attenuation [33, 36, 47, 48]. But research has to be conducted for more in depth understanding.

> The propagation of sound near the ground depends on the surface impedance. Surface porosity and associated air permeability allows sound to penetrate and hence to be both absorbed and undergo

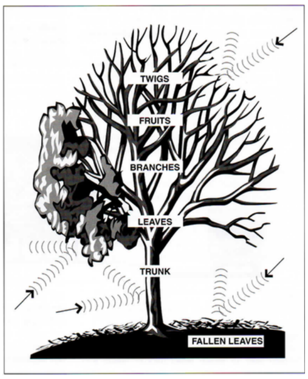



**Figure 2.5:** Illustration of the different effects a tree can have on sound attenuation. Our interest is mainly the litter or fallen leaves component. Because the other components interfere more with the higher frequencies [46].

> phase change through friction and thermal exchanges between the pore fluid and the surrounding solid. The usual assumption in outdoor acoustics is that the ground has a rigid frame and that incident sound waves do not cause motion of the solid particles as well as the pore fluid. There is interference between sound travelling directly between source and receiver and sound reflected from the ground. This interference is known as *ground effect*. — **Attenborough** [49].

This ground effect lies in the destructive interference between the direct and reflected sound wave arriving at the receiver. This frequency dependent effect is most profound in the lower frequency spectrum ($<$1000 Hz).

#### Important parameters

Important parameters to consider in soil acoustics, and used throughout this paper, are flow resistivity $\sigma$, porosity $\Omega$, layer depth $L$ and structure constant $c_s$. Flow resistivity, $\sigma$, is equal to the ratio of the pressure difference to the flow velocity, divided by the thickness of the slab in the case of walls or isolation. This definition is analog to the definition of electric resistance. It indicates how well sound will move in a material (here soil). The porosity, $\Omega$, is the volume fraction of air in the material. Important to consider is that all the pores have to be connected to the atmosphere, otherwise these cannot be reached by incoming sound waves. Layer depth, $L_e$, is a factor that indicates how deep an acoustically rigid layer is found. This is used when a porous material is placed in front or on top of a hard backing. This hard backing material will reflect more sound waves and therefore, has to be defined in the formula or model used. Forest soils are often described as a porous layer on top of a hard layer. The last parameter is the structure constant, $c_s$. This parameter indicates the specific structure of the pores and the frame of the material [23].

### Layered forest soil

Firstly it is important to characterise the forest soil, as it has a specific structure. The main thing to consider in forest floors is the layered structure, see Figure 2.6 this is an example of how a forest soil can look like in temperate, deciduous forests. The effect on acoustics of these layers is pointed out in different studies [50, 51]. For this research the top layers are the most important as it is the top layer of the surface has the most impact on the reflection of sound [51]. The top layers in a deciduous forest are a litter layer where fresh material is seen and under that a decomposed humus layer followed by the mineral layers see Figure 2.6. This gradation happens in the first 10-20 cm of soil [52] so it is important to consider all three.

### Soil and vegetation

Aylor found that by changing the soil the *ground dip* can be shifted to other 1/3-octave bands [33]. This is interesting for the effects of the litter layer on the soil. Furthermore, Aylor did not see a significant impact of loose litter layer on the ground effect, like the pine-needle layer that was studied. Martens et al. suggested that litter layers do not influence soil acoustic characteristics. But, at the end of the paper, suggestions are made about the importance of vegetation on forest soils [53]. Vegetation creates a layered soil structure and in this way changes the acoustical properties. This was found in experiments but not further investigated by Martens et al. Both studies done by Aylor and Martens et al. are older studies, so since then more and more peer-reviewed research on the topic is done. These papers are standard works and therefore mentioned. But the general thought is the layered structure and the potential effect vegetation can have on the soil acoustics.

Dobson and Ryan described the multiple drivers behind ground effect influence by trees. Trees have the capacity to loosen the soil by exploring it with their roots, they create a soft humus layer with their litter and prohibit the soil of becoming dry and hard in summer by shading the soil with their canopy [54].

### Soil moisture

Soils classically hold up a lot of moisture. Especially forest soils, sheltered by the shade of trees, do not tend to dehydrate [55]. Water surfaces (e.g. a lake) reflect almost all frequencies of interest $\alpha = 0.01$ [56], where $\alpha$ is the absorption coefficient. It is thus important to take the moisture into account when research is done on forest soils because it has an impact on sound absorption characteristics [57]. Trends of moisture influence on the flow resistivity found in soils were 200 kPa s $m^{-2}$ at 10% moisture to 1500 kPa s $m^{-2}$ at 35% moisture

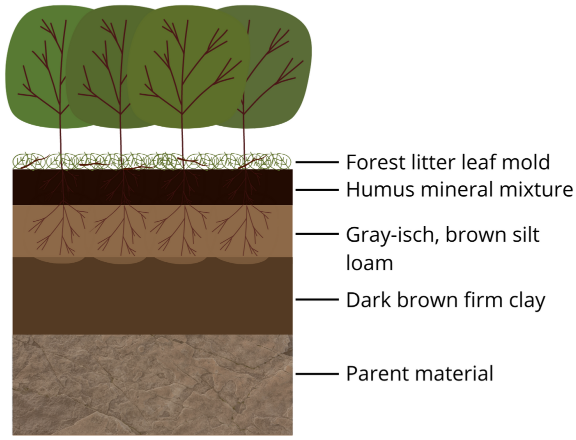



**Figure 2.6:** An example of how different layers of a forest floor in a deciduous temperate climate forest can look like. The layers have an impact on the acoustic behaviour of the sound waves. The layers in the figure are expected in the studied forest.

content. Some remarks have to be made, Cramond and Don did experiments on barren earth and grassland, and soil properties are different from forest soils. The behaviour of moist in forest soils is thus difficult to predict. Reethof, Frank and McDaniel did some preliminary measurements on forest soils, the moisture effect found was increasing absorption effect with increasing moisture [58]. Forest soils are in theory relatively good absorbers with high porosity levels [53]. Martens et al. estimated and measured non-acoustical soil characteristics like, water, air, solid matter content, and porosity, but did not include soil water content corrections. In general there is a lot to discover about the acoustic capacities of forest soils and that is, as described in the following section, the goal of this dissertation.

## 2.6 Research goals

The first objective is to design and test a set-up will for soil acoustic purposes. The goal here is to find a standard method to derive acoustic soil characteristics by conducting acoustical measurements on natural, vegetated soils.
The second objective is to research acoustic soil characteristics of forests. Forest soils have a natural heterogeneity and this is often species induced. Conducting in-situ measurements, collecting data on different parameters and fitting this data to the model tested in the first part of this dissertation, should provide soil characteristics. This to try to find similarities and differences between species and groups of trees that have different litter degradation qualities. With as ultimate goal providing some insight in tree species selection for roadside vegetation.

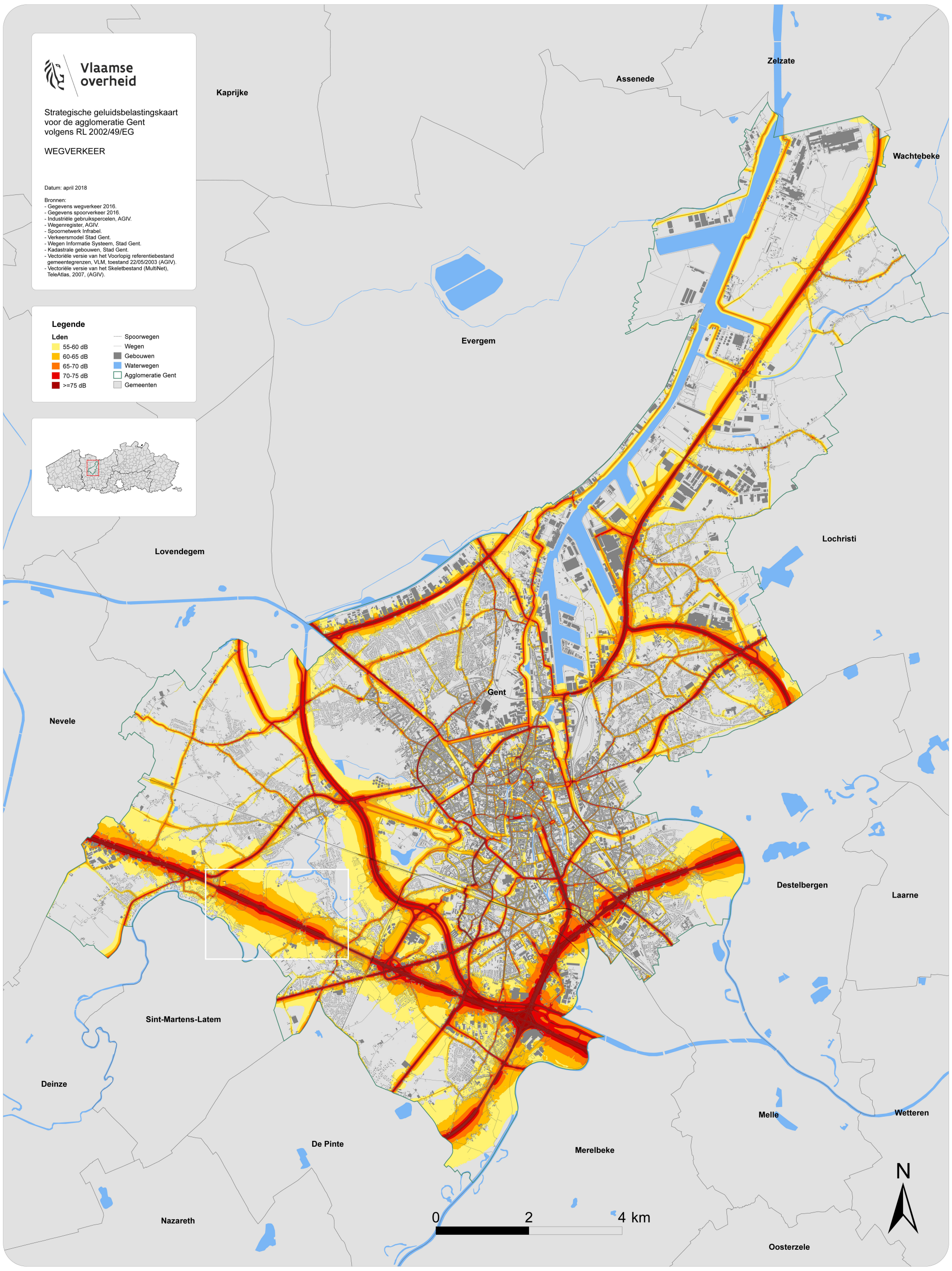



**Figure 2.7:** The calculated amount of noise pollution expected by road traffic in Ghent. The values depicted are the $L_{den}$ values. All the colours are already above the threshold value of 55 dB(A) set by the WHO. Important to notice is that this is a representation of a model output, $f(\#\ of\ cars, speed)$, none of the values indicated on the map are based on noise measurements [59]. The white frame indicates the section of ring road where the earth mount in Figure 2.4 (right) is placed.

# 3 | Material & Method

The goal of this dissertation is, as mentioned in section 2.6, to find a link between the tree species and their effect on the sound reducing capacity of the soil. The method chapter is divided in six sections.

The first section will deal with the theoretical development of the measurement set-up, the physics and underlying mechanisms behind the set-up are thoroughly looked at and explained. In this way a set-up will be designed, by reverse engineering, for the measurement campaign. This part tries to answer the first research question, design and testing of a measurement set-up for soil acoustics. A general overview of the steps followed is found in Figure 3.1, a process flow chart illustrating the different steps and evaluation moments of the set-up design phase.

The second section will describe the study area and explain why this particular area was picked for this in-situ study. In-situ methods are preferred for this measurement campaign over laboratory methods because it is very difficult to simulate the conditions of a forest in a laboratory. The reason for this is that it takes a long time before a forest soil reaches an equilibrium to its final condition.

In a third part the acoustical side of the measurement campaign will be looked at. The section will introduce the different instruments and their settings are explained. The amount of measurements and the way the measurements are organised, concludes this section.

The fourth section will deal with the measurements of the non-acoustical stand characteristics. Additional information on the different variables is given, the amount of samples that are taken and why the characteristics are measured. Followed by a step for step list is shown of the different actions performed at each sample plot.

The last section will give a more detailed description on how the data and results are processed in MATLAB and how reverse engineering is used to find the acoustical soil parameters.

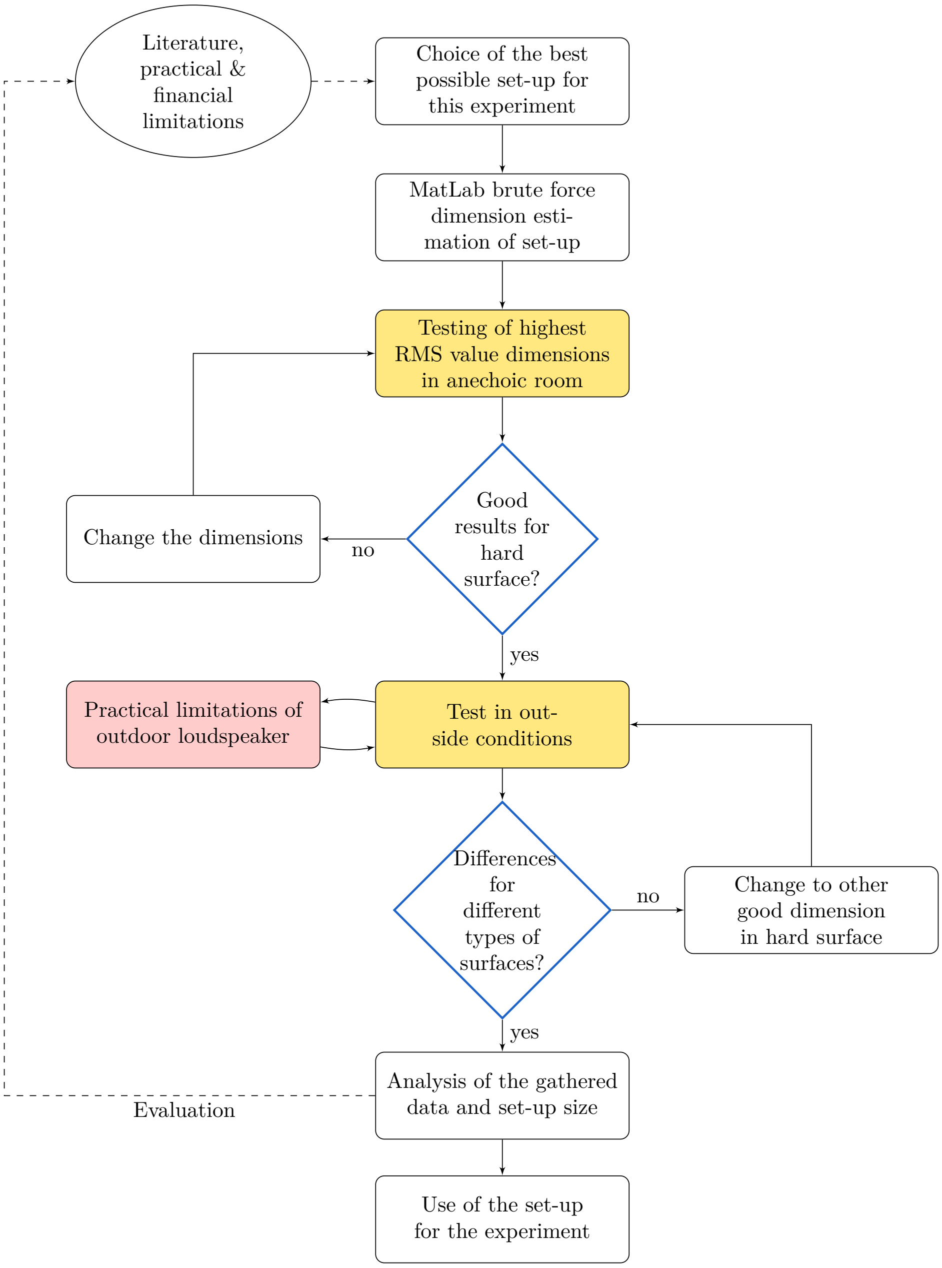



**Figure 3.1:** Flow chart illustrating the different steps and stepbacks that are taken in the designing of the measurement set-up. Yellow blocks indicate experiments, blue diamonds a decision and the red block was the eventual main practical limitation.

## 3.1 Theoretical background of the measurement set-up

For the design and dimensions of the measurement set-up a theoretical approach was needed, see Figure 3.1. This to make sure the set-up would be able to detect the signals in the desired frequency interval. The set-up itself is based on a general way to measure soil impedance. The model uses a point source and two microphones, see Figure 3.2. The theory behind the set-up is actually a short-range propagation set-up [60], done twice. So the two microphones could be seen as if the same experiment is performed simultaneously. The short-range propagation set-up is based on the sound pressure level difference between the sound wave going directly from the source to the microphone ($r_d$) and the reflected wave ($r_r$). Measuring level difference between two microphones rather than excess attenuation has the advantage that information on the free field of the speaker is not required to process the data.

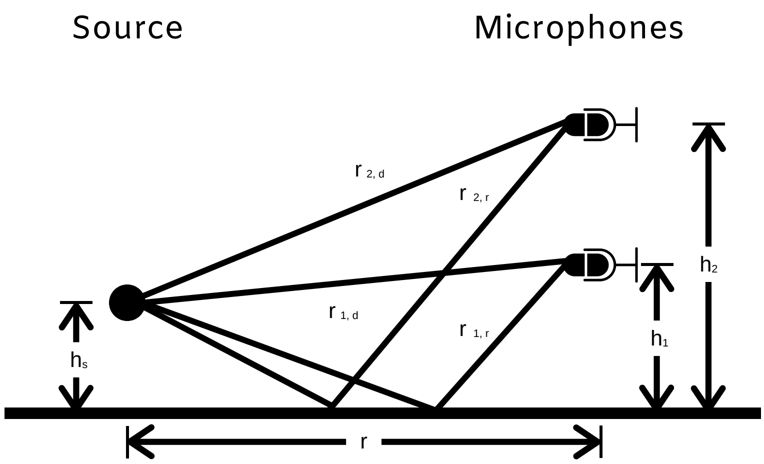



**Figure 3.2:** Schematic representation of the two microphone set-up and the parameters that need dimensioning r, $h_s$, $h_1$ and $h_2$ (after [61]).

When the source produces sound waves, one ray goes directly to the microphone and one goes to the soil. Rays are defined as lines along which the acoustic energy is transported. After reflection on the soil the sound wave moves further to the microphone. The arrival of the reflected wave is delayed with respect to the direct wave by two effects. First, there is a delay due to the increase in distance traveled by the reflected sound path. And for porous layers, the path of the reflected wave, the ground effect induces additional shifts in phase and amplitude. At the microphone three phenomena can be detected: the signal at the microphone can be constructively interfered, destructively interfered and

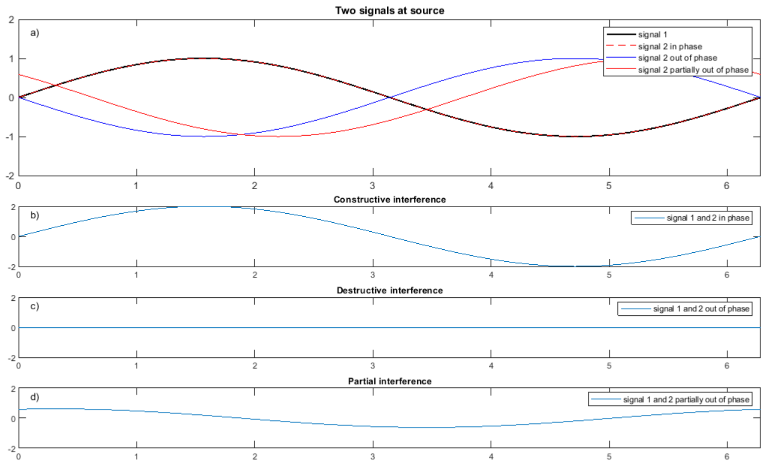



**Figure 3.3:** Here the three forms of wave interference behaviour are illustrated. a) Two signals with the same amplitude, value = 1, are emitted from the source. But for signal 2 in 3 different phase shifts. Now in the next three figures the two signals are added up as they would do when they met in the air. b) The two waves are completely in sync and make the signals' amplitude stronger, value of 2. c) The two waves are completely out of sync and fade each other out as destructive interference occurs. d) Here signal 2 is not completely in, nor completely out of sync with signal 1 and a partial interference occurs.

partially interfered. See Figure 3.3 where this is illustrated. It is eventually this change in interference that causes the large differences in sound pressure level difference detected by the microphones. The behaviour of interference can lead to interesting insights on the ground's acoustical properties.

This destructive interference explains why soft surfaces have a *ground dip* at low frequencies. This can be seen in Figure 3.4, this is an empirical approximation done for the behaviour of one sound source and a receiver. For this approximation the soil parameter $\sigma$ or the flow resistivity was used, the most important parameter for a porous surface. In the figure it is seen that the signal slowly fades out for the higher frequencies, but this is merely an effect of destructive and constructive interference averaging each other out. A hard ground surface also has a ground dip but this occurs at much higher frequencies that lie outside of the spectrum of transportation noise, Figure 2.1, and therefore useless in practice.

It is known that a forest floor behaves as an *acoustically soft* surface [62], this means that when a sound wave hits the surface it can penetrate the soil up to a certain extend, 10 cm [51], and interact with the soil in the pores. Sound waves are changed in amplitude and phase. In general, the larger this delay the

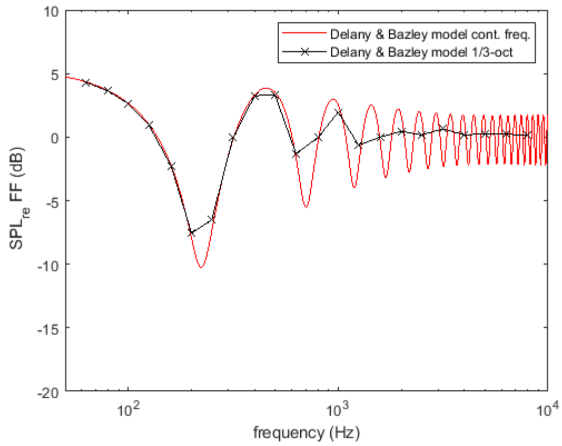



**Figure 3.4:** The Bazley and Delany model is used to show how the sound wave and the signal received at the microphone behaves for the different frequencies. On the y-axis, the real part of the sound pressure level in dB is shown. In this figure $\sigma = 100$ kPa s m$^{-2}$, distance between receiver and source = 5 m, source height = 1 m and receiver height = 1.8 m. The black line illustrates how the 1/3-octave bands average differences over frequencies.

more porous the surface and this causes for the change to lower frequencies of the *ground dip*. This is also the case for *acoustically hard or rigid* surfaces but they show the first destructive interference at much higher frequencies.

For reflecting waves, if the propagation direction of the incident wave is not normal to the ground then the propagation direction of the transmitted wave is, in general, also not normal. But it is a good approximation to assume that it is normal, irrespective of the incidence of the incoming wave [23]. These surfaces are called locally reacting ground surfaces, this to simplify model and calculations. That is why further in chapter 3 the acoustical properties of the soil can be represented by its relative normal-impedance, $Z_n$ (See Equation 3.1, 3.2 and 3.7) and the ground forms a finite-impedance boundary. Measurements are done at both microphones, deducting these measured values gives $\Delta L$. With this $\Delta L$ the effect of the ground on the impedance can be found per frequency. The advantage of performing a two microphone level difference experiment is that no atmospheric attenuation has to be considered. Atmospheric attenuation originates from two effects: thermal conduction and viscosity of air and relaxation losses of oxygen and nitrogen molecules in air. In this set-up the two microphones are close to each other, thus atmospheric effects can be considered equal for both.

But, the wind is a factor that can have an effect on the measurements as wind induced noise. To minimize this, the measurements were done on days with low wind speeds, preferably <5.5 m s$^{-1}$, see Table B.1. To further minimize wind effects an extra wind shield was placed over the microphones.

### 3.1.1 Two-ray model

The total pressure received at a microphone is composed of a direct and a reflected sound ray, see Figure 3.2. The two-ray model is a model that generates a sound pressure level spectrum at the microphone. The model uses the position of the source and microphone together with the ground characteristics to predict the way a sound wave will interact with the ground for that specific geometry. This interaction is determined by the spherical wave coefficient, $Q$. This spherical wave coefficient is dependant of the height of source and microphone, distance between the two, the wave number k for a specific frequency in air and $Z$, the relative impedance factor. It is this $Z$, that is provided by the models in the next section. More specifically it is $Z_n$, because the assumption of normal incidence was made in the previous section.

### 3.1.2 Proposed impedance models

Firstly the one-parameter Delany & Bazley-model (D&B) for characterisation of the relative impedance factor $Z_n$ was used, see Equation 3.1 [63].

$$Z_n = 1 + 0.0511(\frac{\sigma}{f})^{0.75} + i\,0.0768(\frac{\sigma}{f})^{0.73} \tag{3.1}$$

Where $Z_n$ is the relative specific acoustic impedance, $\sigma$ is the flow resistivity and $f$ is the frequency. This model usually can, despite having only one parameter, fit the data rather good on grassland soils and they provide a value for the flow resistivity. This model is originally developed for rock wool but performs well on grasslands, so it lies outside its range of use for forest soils. Nevertheless, the model will be used for data fitting because it is very simple and straightforward.

As mentioned in the Nordtest-method there is also an extra factor that can be added to the model [64, 65]. A rigid backing could improve modeling (see Equation 3.2), the rigid backing is expected to be the mineral layer under the, rather soft and porous, litter layer. Measurements conducted by Martens et al. found values of $>$400 000 Pa sm$^{-2}$ for the mineral soil layer just below the organic layer (for more info on the forest layers see Figure 2.6). This study indicates that the mineral soil can be described as an acoustically rigid layer. The addition of a best estimated depth of the hard layer changes the $Z_n$ value, see Equation 3.3. This suggestion, made by Attenborough, Bashir and Taherzadeh [66], is also confirmed by Taraldsen and Jonasson [65], who researched the importance of a rigid backing in simple, one or two parameter, models for soils.

$$Z_n = Z_{n1} i \cot{(L_e k)} \tag{3.2}$$

$$k = \frac{2\pi f}{c}\left[1 + 0.0858(\frac{\sigma}{f})^{0.70} + i\,0.1749(\frac{\sigma}{f})^{0.59}\right] \tag{3.3}$$

Where, $Z_{n1}$ is the $Z_n$ found with Equation 3.1; $L_e$ is the best estimated depth of the hard layer and $k$ is the wave number in the material, here soil or litter.

But D&B is an empirical model, its variables were fitted to measured data and not necessarily physically correct. In a next step the Zwikker & Kosten (Z&K) or also called phenomenological (ground) model is used Equation 3.7. This model is based on physical more correct assumptions and no error against the conservation of energy is made, in contrary to D&B, as was found in another research [67] by Taraldsen.

$$k = \frac{\omega}{c}\sqrt{q_c\Omega} \tag{3.4}$$

$$Z_n = \sqrt{q_c/\Omega} \tag{3.5}$$

$$q_c = \frac{c_s}{\Omega} + i\,\frac{\sigma}{\rho\omega} \tag{3.6}$$

$$Z_n = \sqrt{\frac{c_s}{\Omega^2} + i\,\frac{\sigma}{\rho\omega\Omega}} \tag{3.7}$$

Where $Z_n$ is the relative specific acoustic impedance; $\sigma$ is the flow resistivity; $f$ is the frequency; $c_s$ is the structure constant; $\omega$ is the angular frequency; $\rho$ is the density of air (=1.2 kg m$^{-3}$); $\Omega$ is the porosity and c is the speed of sound in air (=340 m s$^{-1}$). These specific acoustic impedance values are an approximation of the wave behaviour. It is clear that this model has more parameters that can be used to study the soil effect. For this model it is also possible to add a hard backing. This is done in the same way as in Equation 3.2, this is final step in trying to improve the fitting results. This model is physically the most correct while it also has the element of a rigid backing implemented.

Looking at the literature, an important thing to point out is that Attenborough, Bashir and Taherzadeh also found that the characterisation of the forest acoustic variables is challenging with short-range propagation models like Delany-Bazley (Equation 3.1 & 3.2). The model provides good results for grass-covered surfaces but tend to have more difficulties with *softer* undergrounds. Some good results were found with and Zwikker & Kosten (Equation 3.7) with hard backing in forests.

Everything considered, the two microphone set-up is simple, practical and could be effective for the experiment in this thesis. It has shown its versatility and robustness over the years in numerous researches [57, 60, 61, 68].

### 3.1.3 Evaluation

Evaluation of the accuracy of the models will be done by the RMSE, see Equation 3.8. In this formula a minimal value will be looked for in a brute force method to find the correct parameter values. This root mean square calculates a minimal difference between the measured data points and the predicted values by the model.

$$RMSE = \sqrt{\frac{\sum_{f_c}(\Delta L_m(f_c) - \Delta L(f_c, model\, parameters))^2}{n_{f_c}}} \tag{3.8}$$

Where, $\Delta L_m(f_c)$ is the measured difference; $\Delta L(f_c, model\, parameters)$ the predicted difference over the 1/3-octave bands; $n_{f_c}$ is the number of 1/3-octave bands and $f_c$ the center frequency of an 1/3-octave band. RMSE gives an average mistake over each 1/3-octave band in dB $f_c^{-1}$.

As a second evaluation, the NT error, see Equation 3.9, defined in the Nordtest method and also used by Attenborough, Bashir and Taherzadeh is calculated [66]. This is simply the sum of the absolute differences between the calculated value by the model and the measured data. It gives an idea of the overall misfit of the model. Nordtest gives an error threshold value of 15 dB. If it is surpassed, the impedance model is not valid. Important to consider is that this is for fewer octave bands, 12. Fitting in this thesis is done for more than 12 bands, 25 Hz-2.500 Hz, because of the interest in lower frequencies. But for the error in Equation 3.9, the same 1/3-octave bands are selected as the ones used in the Nordtest-method. In this way model fitting in this thesis can be compared to measurements done by other scientists.

$$NT\, error = \sum_{f_c} \mid (\Delta L_m(f_c) - \Delta L(f_c, model\, parameters) \mid \tag{3.9}$$

Where, $\Delta L_m(f_c)$ is the measured difference; $\Delta L(f_c, model\, parameters)$ the predicted difference is over the 1/3-octave bands and $f_c$ the center frequency of 1/3-octave bands. It is thus the accumulated error over the 1/3-octave bands.

### 3.1.4 Dimensioning the set-up

#### Geometric parameters

To construct the set-up, a model was needed to predict the signals captured by the microphones. And this for different soil characteristics and set-up dimensions. The following parameters were all used to maximize the signal differences at the microphones, as seen in Figure 3.2:

- Distance from source to microphones (projected on the floor): r
- Height of the source: $h_s$

- Height of the microphones (different for microphone 1 and 2): $h_1$ & $h_2$

These were used to find an optimal set-up. To be able to find a maximal difference in the frequency spectrum of interest, a brute force method was performed with MATLAB [69]. A combination of a different combinations of dimensions was tested. The main constraint of this brute force was the practicality of the set-up. So no values higher than 2 m where used because this would make the set-up very hard to handle given the fieldwork that will be discussed below, in section 3.3. So the parameters $h_1$, $h_2$ and $h_s$ where looked at for the interval 0-2 m and r for 0-2 m later on the size of this interval was decreased because there has to be at least some distance between the source and the microphones. Because placing receivers in the near-field region, makes it difficult to assume point source behaviour. Near field is the region close to the source where the sound pressure level does not follow spherical or cylindrical spreading [70].

The step size for the dimensioning was 0.1 m. So the brute force method performed a quantification with as quantifier the Root Mean Square (RMS) of the difference between the upper and lower microphone, the $\Delta$L. The RMS was calculated for the 1/3-octave band frequencies of interest between 25 Hz and 2500 Hz, the idea is that the difference between upper and lower microphone should be maximal so to find a broader spectre in parameters and thus easier distinguishing between species. The model used for the dimensioning is the more physically correct Z&K model.

**Acoustical soil parameters**

For the structure constant, one of the variables in the Zwikker & Kosten model, see Equation 3.7, the value was set on 1 because the value does not have a big impact on the RMS.

Flow resistivity value was set on 20 kPa s $m^{-2}$, a value found in the literature and a good approximation of a forest floor [71, 72]. In later studies a range was suggested from 9 to 200 kPa s $m^{-2}$ [66] but this was derived from non-acoustically measured values. So, the original value was kept. The value of 20 kPa s $m^{-2}$ is also close to values found by Attenborough for beech soils. Additionally, this was also one of the only values found for broad-leaved species.

As a last and important acoustical characteristic in the Zwikker & Kosten model the porosity of the soil has to be looked at. To get an idea of optimal dimensions two different values were found in literature: 0.4 and 0.8, with 0.4 being a very low and 0.8 being a very high level of air filled porosity for a forest floor [66]. From the same paper, [72] the value of 0.5 for the porosity was picked. This is something in between 0.4 and 0.8 and thus would give good results for both cases. The porosity together with the value of the flow resistivity, are the main objectives to determine from the field experiment. Furthermore the value was also found in the paper of Attenborough, Bashir and Taherzadeh for beech soils.

The depth of the rigid layer was not taken into account for the dimensioning of the set-up.

**Nordtest**

The own attempt of dimensioning a set-up resulted in poor results. The two-ray model assumes that the used source is a perfect point source. A perfect point source is a source that emits exactly the same acoustic energy in all directions. But the source used in the set-up is not a perfect point source, thus cannot emit the same amount of sound energy in all directions. Because the microphones are placed far from each other, the incoming direct energy is different and the model does not hold anymore. This practical limitation of the loudspeaker, seen as a red block in Figure 3.1, was the reason the literature was looked at. A standardized method was found: The Nordtest Method [64], developed by Nordtest. This method provides dimensions, see Table 3.1, for a set-up that can derive the soil impedance $Z$ in-situ for flat outdoor surface with a two microphone approach. The method is optimized for the frequency range between 200-2500 Hz but for this thesis is expanded to 25-2500 Hz. To include the full spectrum of interest, see Figure 2.1. Furthermore it was questioned if the Nordtest method could be improved for fitting forest soils with their ground dip classically in the lower frequency range. The choice for the Nordtest method was well considered, given the already shown evidence of its performance [65, 66].

**Table 3.1:** Overview of the dimensions of the Nordtest method as it was proposed by the Nordtest team. These dimensions are standardized and should perform optimal for outdoor (natural) ground surfaces [64].

| Parameter | Length |
|---|---|
| Source height | 500 mm |
| Bottom microphone height | 200 mm |
| Top microphone height | 500 mm |
| Horizontal separation source-receiver | 1750 mm |
| Extra microphone height[1] | 700 mm |

The selected method is thus the Nordtest method with standard dimensions, [64]. Before measurements were conducted outside, the set-up was checked in the anechoic room on a hard surface to validate if the model would stand. Also some outside tests were conducted with these dimensions to check whether high

[1]This height is not part of the Nordtest method but is added as a supplementary measurement and used for a validation step.

SNR values are seen, the model could fit the data and if parameter values could be conducted.

## 3.2 Description of the study area

The relevance of an in-situ experiment is already explained in the introduction of the Material and methods section, chapter 3. The fieldwork has been done at Mortagnebos, Sint-Denijs (West-Flanders, Belgium), see Figure 3.5. The forest has an area of 13.02 ha and the owner is OCMW Kortrijk, but the management is done by *Agentschap voor Natuur en Bos* (ANB) of the Flemish Government.

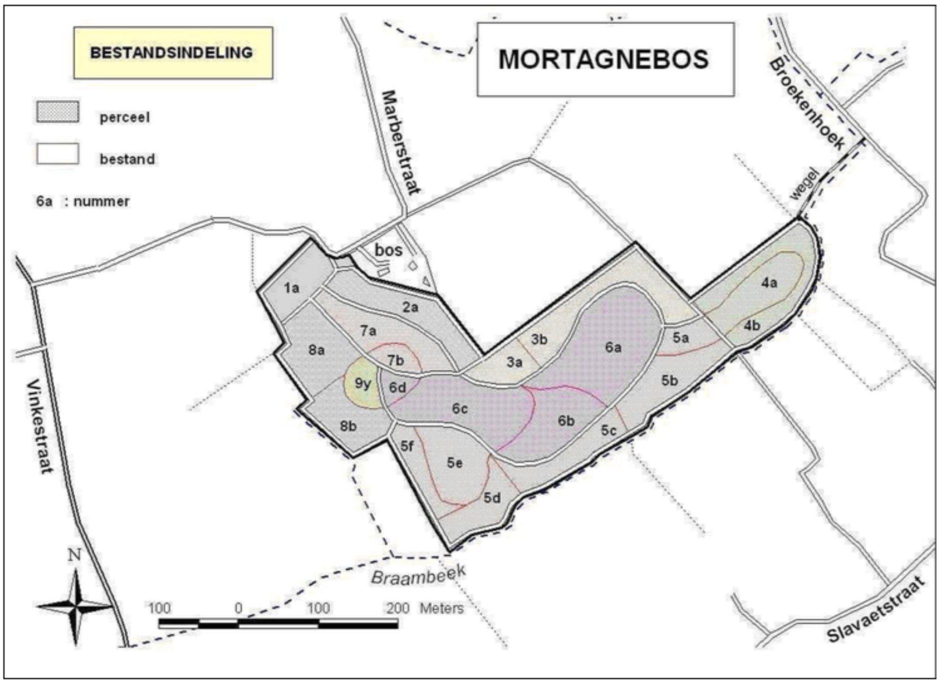



**Figure 3.5:** Map of Mortagne-forest and how it is separated in different stands [73] Sampling was done in the following stands: 1a, 5a, 5c, 6a, 6c, 8a.

The research goal is to find differences between diverse species, therefore the forest has to have monoculture stands. To make valuable conclusions about the species effect on the soil, it is preferable that the climate, soil and history of use should be more or less the same. Furthermore, the planting date and scheme should be at the lowest grade of variance.

The Mortagne-forest, *Mortagnebos*, ticks almost all boxes, this forest consists of nine different deciduous species monoculture stands, see Table 3.2 and Figure 3.5.

**Table 3.2:** Different tree species planted in Mortagnebos in 1971. The table also mentions whether or not the tree species will be sampled and if yes, the litter quality class. (Y = yes and N = no) and the stand ID, as seen on the map of the Mortagnebos Figure 3.5.

| English name | Scientific name | Sampled? (litter quality) | Stand ID |
|---|---|---|---|
| beech | *Fagus sylvatica* | Y, poor degrading | 6c |
| black locust | *Robinia pseudoacacia* | N | - |
| common alder | *Alnus glutinosa* | N | - |
| northern red oak | *Quercus rubra* | Y, poor degrading | 6a |
| pedunculate oak | *Quercus robur* | N | - |
| small-leaved lime | *Tilia cordata* | Y, intermediate degrading | 5a |
| sweet cherry | *Prunus avium* | Y, good degrading | 5c |
| sycamore maple | *Acer pseudoplatanus* | Y, intermediate degrading | 8a |
| white ash | *Fraxinus americana* | Y, good degrading | 1a |

The soil of large parts or the forest is of soil type Ada[2].

Only the south-eastern stands, sweet cherry and small-leaved lime, lie in Adp[3]. The *A* stands for loamy soils, *d* represent the draining class. The soils are moderate gleyic, the difference lies in the last letter. Ada has a reduction horizon at 80-120cm and Adp has no profile, probably a relict of the agricultural past, as is seen in Figure 3.6. Both fall under the Luvisol category of the World reference base for soil resources (WRB) [75]. Differences between the two soil types lie in the deeper layers, so it is assumed this will not affect the measurements. Talaske found that sound interactions take place in the upper 10 cm. Further assumptions are made for the macro-climate. The forest covers only a few hectares, so long-term weather conditions are assumed constant in space. The significant effect on the forest soil is expected to be driven by the tree species, as this is the main difference between the stands [76–79].

## 3.3 Acoustical part of the field work campaign

The fieldwork consists of two major parts. The acoustical part, of which the measurement set-up is already theoretically explained, and secondly the forest variables, in the next section often referred to as the non-acoustical measurements. Firstly the practical side of the sound experiment will be discussed.

[2] *matig gleyige leemgronden met textuur B-horizont (5) in éénduidige legende voor de digitale bodemkaart van Vlaanderen* [74]

[3] *matig gleyige gronden op leem zonder profielontwikkeling (3, 5) in éénduidige legende voor de digitale bodemkaart van Vlaanderen* [74]

**Figure 3.6:** Situation in the Mortagnebos just before (left) and just after planting (right) the trees in 1971. The planting pattern is visible in the right picture when looked at closely [80, 81].

**Figure 3.7:** Picture of the measurement set-up as it is used, this set-up example has the Nordtest-method standardized dimensions. From left to right: the metal frame, microphones, and source.

### 3.3.1 Material used for acoustic measurements

The specifics of the used devices/materials will be summed up in this section, also see Figure 3.7. Description of the full specifics are of course not possible but the most important ones for this dissertation will be mentioned.
The source is a portable loudspeaker of JBL type FLIP 3 black edition with following specifications, 2x8 W output power, 85 Hz - 20kHz frequency response, SNR-ratio ≥80 dB [82]. The source was connected to a mobile phone through a 1.5 MM Stereo Jack Audio cable where a signal was played.
The signal was generated with MATLAB's `mataa_signal_generator` function. The signal generated lasts for 20 seconds, is pink[4] noise and has a frequency sampling rate of 48kHz. It is saved as an .wav-file to ensure no quality was lost, because a .wav-file is a raw and uncompressed audio format.
The two microphones used are two 1/2" free-field type-1 microphone capsules

[4] In pink noise, each octave (halving or doubling in frequency) carries an equal amount of noise energy.

4189 from Brüel and Kjær, with a nominal sensitivity of 50mV/Pa over 6.3-20000 Hz and with dynamic range of 14.6-150 dB. It has a relatively flat response curve in the frequency interval of interest [83].
These capsules are attached to a SV12 preamplifier of SVANTEK [84]. Over the microphone and first part of the preamplifier a windscreen is installed.
These are connected to class 1 SVAN 959 sound pressure level meters [85]. The settings of the SVAN 959 were: 200ms interval measurement, a datalogger writes everything onto a USB drive, linear integration of the measurements and manual start of logging. The SVAN959's were calibrated everyday with a SV35A calibrator that produces an acoustic pressure of defined level 94 dB at frequency of 1kHz. This calibrator has a microprocessor controlled signal source including digital static pressure and temperature compensation, so no temperature or pressure adjustments have to be made [86]. Connections between the microphones and the SVAN 959 devices were made with short coax-cables and BNC-connectors.

### 3.3.2 Acoustic measurements

The number of measurements that will be performed is linked to the number of stands and the fact that there is a natural heterogeneity in forests. Because of this heterogeneous character of forests, conclusions cannot be made from one sample plot in a stand. The more sample plots are measured, the larger the amount of evidence but due to limited time, the stand is represented by two sample plots. So at two locations within the stand, acoustical and non-acoustical measurements will be made. This, in an effort to get a more holistic idea of how the species affects the forest soil. Six stands are selected, see Table 3.2 and Figure 3.5, these will be inspected thoroughly in situ. In this way, flat surfaces with little vegetation and low stem density can be selected as sample plots. Furthermore, the edge effect has to be taken into account, so edges are excluded from sampling.

Since exact distances are important for the two microphone model to be used. The theoretical set-up as seen in Figure 3.2, is placed on a metal rectangular frame, see Figure 3.7 & 3.8. In this way the set-up can be placed over and over again, transported to other stands and turned around without having to reposition the source or microphones.

To make sure enough acoustical data is acquired, the following idea is presented. An acoustical measurement will be done at each sample plot. Then the set-up will be turned around 90°, this to have a repetition for the same forest soil and to rule out some of the very local variances. In this way multiple acoustical measurements are done for each species and these can be combined to get a mean value for a certain soil type. As an extra measurement these steps are also performed for a different height of the upper microphone. These extra measurements could be interesting in the fitting of the model to the data, because extra data can be added. The physical modelling can then be performed on two sets, which in theory, could improve fitting. Or be used as a validation as is done for this thesis. The objective is to end up with one set of values for the acoustical parameters for a certain stand.

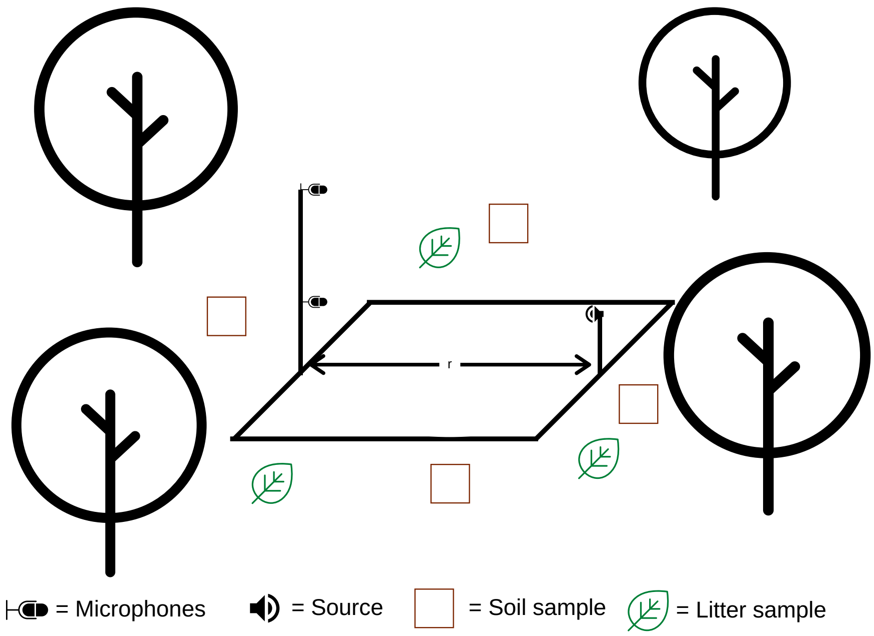



**Figure 3.8:** Schematic representation of the measurement set-up in the forest. The soil samples ($N = 4$) are taken outside of this rectangle (with r = 1.75m) to make sure the soil remains undisturbed as much as possible. Analogue, the litter samples ($N = 3$) are also taken outside the rectangle.

In addition to the measurements on top of the undisturbed forest floor, measurements are also performed at the same location after the litter and humus layer is removed. This is based on an experiment of removing the litter layer done by Reethof, Frank and McDaniel [58]. Practically this is executed by manually raking away the leaves and humus layer until only the topsoil layer is left. once the litter layer was removed, the same measurements are performed (reference measurement, set-up turned 90 °and one microphone higher) in this way, the impact of the litter layer can be characterised. The litter layer is presumed to be the key factor of the sound impedance so this practice could be regarded as one of the most interesting parts of the experiment.

## 3.4 Measurement of the non-acoustical stand characteristics

The field work for the forest variables is organised in a similar way, but of course other samples are collected. The following variables are expected to have an impact on the acoustic characteristics of the soil:

- Litter biomass
- Soil density
- Soil moisture content
- Litter moisture content
- Herb layer vegetation cover
- Tree density

Simultaneously with the sound experiments, the collection of forest soil characteristic data gathering will be done on each selected plot. In this way a link could be found between the above enlisted variables and the sound mitigating effects of the soil. To finally be able to link the effect of tree species or, more general, the effect of the litter layer quality class caused by the tree species on the impedance of the soil.

In the next part, the way the different variables and data have been measured, is explained more in detail.

### 3.4.1 Litter biomass

Depending on the nutrient composition and degrading speed, literature research [87–89] led to three different classes of litter quality: good, intermediate and poor degrading litter. For each class two species are selected in the forest, see Table 3.2. This, rather artificial, division is to make general remarks about the effects of a litter quality class, rather than a pure species effect. The poor class consists of beech and northern red oak. Two species with a dense litter layer and classified with moder humus. The other species are more difficult to distinguish as sycamore maple and lime for example are often categorized as fast degrading litter species [88, 90], but make up the intermediate litter quality class in this thesis.

Most of the material in the litter layer comes from the trees. So, the nutrient content of the leaves will be decisive for the degradation speed and chemical composition of the soil [76, 77]. Therefore, the litter layer is expected to be the component that makes the soil of the different tree species visually and chemically distinguishable, as Wittich suggested many decades ago [79] and is also quantified by Binkley and Giardina. Differences between species for litter fall mass reach up to 20-30 % [91]. Because of the high difference between species,

$N = 3$, litter samples are taken at all sample plots. A 20cm by 20cm square, see Figure 3.9, is used as measurement equipment to guarantee a consistent volume of litter is taken. To determine the biomass of the litter, it is sieved, dried, as explained in subsection 3.4.3, and weighed. The dry litter makes up the biomass in gram.

### 3.4.2 Soil density & soil moisture content

For the soil type the *Bodemkaart: bodemtypes* of the Flemish government is used [52]. Soil samples are taken after the litter layer is removed, in this way the litter has no influence on soil moisture content. For the soil sampling method, the manual of the *Instituut voor Natuur- en Bosonderzoek (INBO)* is used as a guidance [92]. To get representative samples for the underground at each sample plot, they are taken in the area around the set-up, as is seen in Figure 3.8.

To determine the moisture content the oven-dry method is used. Therefore a sample core of a known volume has to be taken. This is done with the 100 cm$^3$ Kopecky-rings, see Figure 3.9 (left). Kopecky-ring samples are taken at each plot, ($N = 4$), and emptied and sealed in plastic containers. Samples are first weighed moist. Then put in an oven for 24h at 105-110 °C to make sure all the water evaporates. The oven-dry soil is weighed again. The difference between dry and wet soil is used to calculate the gravimetric water content ($\theta_g$), Equation 3.10. The average is taken of the four samples to represent the plot.

It is known that water content has an effect on sound absorption [61, 93]. Therefore water content is calculated to be able to link water content to the acoustic measurements in a later stage.

Furthermore the bulk density ($\rho_{bulk}$) is calculated as well (Equation 3.11). A small example is given together with the formulas and following data:

| | |
|---|---|
| $m_{wet}$ | $132.32g$ |
| $m_{dry}$ | $67.27g$ |
| $volume$ | $100cm^3$ |

$$\theta_g = \frac{m_{wet} - m_{dry}}{m_{dry}} = \frac{132.2g - 67.27g}{67.27g} = 0.97 g_{water}\, g^{-1}_{dry\,soil} \tag{3.10}$$

$$\rho_{bulk} = \frac{m_{dry}}{volume} = \frac{67.27g}{100cm^3} = 0.67 g\, cm^{-3} \tag{3.11}$$

where, $M_{wet}$ is the mass of the wet litter sample & and $M_{dry}$ the mass of the dry litter sample both in grams, the volume of 100 cm$^3$ is the size of the Kopecky-ring Figure 3.9.

**Figure 3.9:** Kopecky rings used for gathering soil for the calculation of the moisture content, are typically 100 cm$^3$ (left) [94] A sampling square that is used to make sure every time the same amount of litter is observed and collected. The one used is 20X20cm (right) [95].

### 3.4.3 Litter moisture content

As mentioned, trees are the direct driver of the litter layer. The litter collected for the biomass is also used for calculating the moisture content. Litter can hold up quite a lot of water [96]. Similar to the soil samples, litter samples ($N = 3$/sample plot) are collected in plastic bags, sealed, weighed and dried. The drying lasts 24 hours at 65°C. Then the samples are weighed again and moisture content is calculated with Equation 3.10, the same as used for the soil. No exact volume can be measured here, so bulk density can not be calculated. The average of the three samples represents a sample plot.

### 3.4.4 Tree density & herb layer vegetation cover

At last, and this is merely to characterize the forest, a vegetation and basal area measurement done in a Fixed Area Plot (FAP) of 100 m$^2$. With this data, the forest or the stands can be characterized and the reader has a more detailed idea of what the different stands look like. When the stand is very dense it can also have an effect due to scattering or reflecting the sound waves. Although these effects are not desired for this study, it is beneficial for sound mitigation in general [7]. But for the measurements it can have a divergent effect. Also the vegetation could have an effect when there would be a lot of dense vegetation on the soil. Although Reethof, Frank and McDaniel did not find conclusive findings on this matter [58], this is not desired for the acoustic measurements. Because the pure soil effect is the scope of this research.

**Figure 3.10:** Example of manually removing the litter layer of a sample plot of northern red oak, *Quercus rubra*, to measure the acoustic properties of the bare forest soil.

## 3.5 Steps at one plot

Here a short summary of the steps at one plot is given, a sort of manual of the fieldwork:

1. At the start of a measurement day, calibrate the two SVAN 959 sound level meters with a SV 35 Class 1 Acoustic Calibrator at 94 dB level.
2. Test the microphone with the test signal of the calibrator of 94 dB and 114 dB.
3. Place measurement set-up at a suitable location (see section 3.4). And install source and microphones at correct height.
4. Perform different acoustic measurements as described above, e.g. Nordtest dimension, microphone at different height, turn the set-up 90°, rake away the litter layer, see Figure 3.10, and repeat acoustic measurements. Write down all timestamps of the measurements (see Figure B.1).
5. Take soil and litter samples directly around the set-up to make sure the samples are representative for this sample plot and acoustic measurement.
6. After series of measurements, control if the calibration of the SVAN 959 is still accurate. This can be done by measuring the SPL of the calibrator, should give 94 dB, with an accepted error of 0.5 dB.
7. Weigh all the litter and soil samples immediately after arrival. Put in the oven to dry at the correct temperatures.
8. Weigh the samples when dried.

## 3.6 Data processing

In this section some additional information and figures on the process of data analysis, the model and post-measurement processing is given.

All measurements are found as .svn-files on a USB drive, plugged into the data logger. Detailed information on the instruments can be fond in subsection 3.3.1. In Table A.1 the raw output of the logger data is seen. To easily load results in the MATLAB environment, all measurements are transferred to Excel formats.

### Separation of signal and noise

The measurements were all made in the frequency spectrum from 20 Hz to 20 kHz, the audible range of the human ear. First of all they are cropped to the 25-2500 Hz range of interest. The measurement consists of a background noise recording, then three signals each paused for ten seconds. These pauses are needed to record more background noise, an example of a complete measurement is seen in Figure 3.11. The measurement of the background noise is important in a later step where this will be used to make a distinction between signal and noise (SNR).
In order not to lose too much time looking for signals and background in the

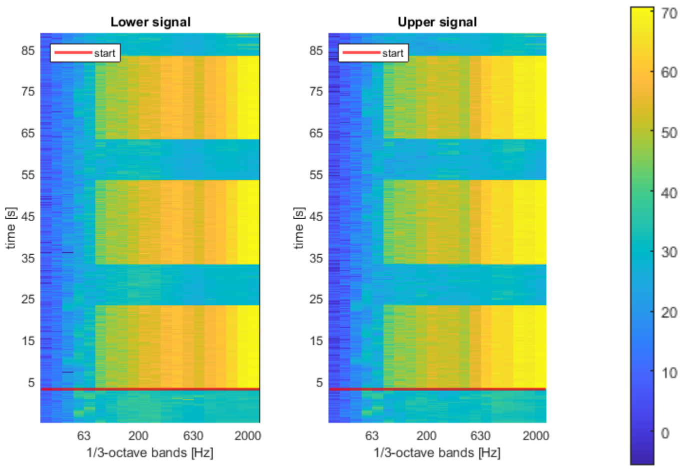



**Figure 3.11:** Different frequencies on the x-axis, the time of the measurement on the y-axis. And the colors indicate the dB levels, see scale on the right, measured at the microphone for a specific 1/3-octave band. Starting point of the signal (red line), at ≈5 seconds, and the rough data of the whole measurement plotted. Here the three signals and noise are clearly distinguishable. The three bars of signal all last 20 seconds and the background noise measurements in between only 10 seconds.

data, the following method was used. The start of the signal is detected as a sudden jump in the dB(A)-value, this accords to the moment the source starts playing the signal. A threshold value of 15 dB(A) is chosen for this jump, this because in the Nordtest method was instructed that the background noise and the signal should differ at least 15 dB(A). As is seen in Figure 3.11 it is clear that this automatic way of finding the start of the signal is accurate. This is done for the two microphones separately so the start and the end of the signals match as much as possible. Finding the start of the signal for each measurement is needed since there is always a, human induced, lag between pressing the button to start logging on the two SVAN 955A devices.

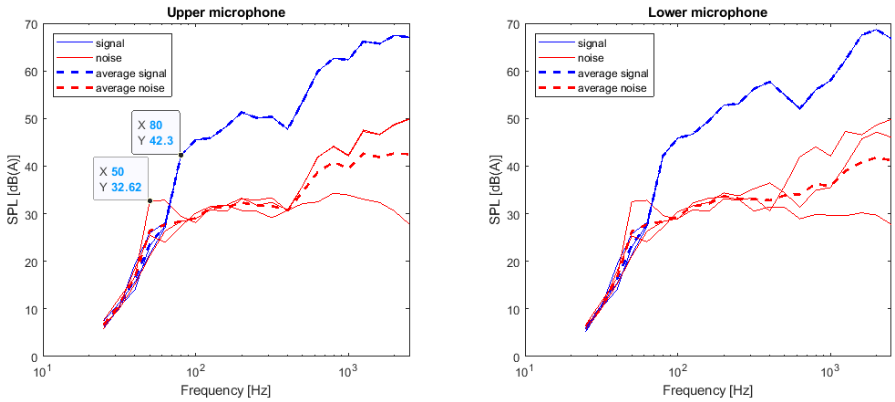



**Figure 3.12:** The signal (blue) and noise (red) averaged over the different 1/3-octave bands as measured during a field campaign measurement. The dashed lines are the averages of the three signals and noises, blue and red respectively. Two values are pointed out because these are the threshold values for the SNR-ratio seen in Figure 3.13. In that figure, there is no value below 80 Hz because the average noise is higher than the average signal, seen in the figure seen here.

The measurement and the signal background noise are then separated and looked at more into depth. The three signals and the noise are averaged over the different 1/3-octave bands. This is the thicker, dashed line in Figure 3.12. When there is a signal emitted by the source, the average value of the noise is deducted from the average value of the signals. In this way a signal-to-noise ratio (SNR) can be calculated for every 1/3-octave band. Next, the SNR is tested if it is higher or lower then zero. When higher, this band is used for the fitting of the model. The value of 15 dB(A) mentioned above is still valuable because this was to detect the signal and the assumption is made that this will be the case for the rest of the measurement as well, is seen in Figure 3.13. When lower a not a number (NaN) value is appointed to this band in order not to disturb the fitting process. The values of the SNR higher then zero are seen in Figure 3.13. But if this is a bit lower than 15 dB(A) the measurement will still be valuable, but less convincing.

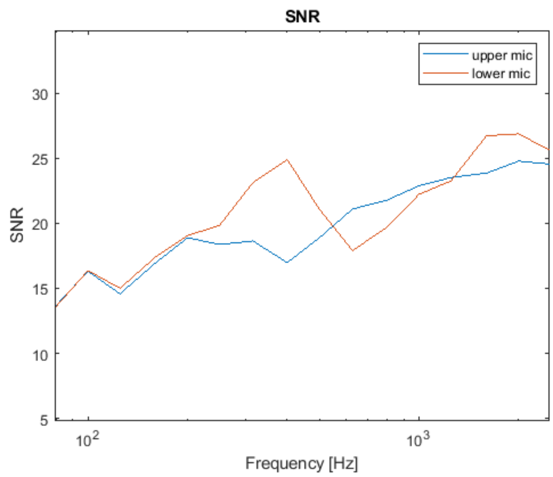



**Figure 3.13:** SNR is displayed over the 1/3-octave bands. The values under 0 are left out, when the noise is higher than the signal (see Figure 3.12), that is why there is no value below 80 Hz. Since, the loudspeaker is not able to produce sounds at very low frequencies.

### Brute force method fitting

The data is fitted with the models presented in subsection 3.1.2 by running a MATLAB code over the data. Figure A.1 illustrates the way the MATLAB function works. What the function does in words, is going over all the different possibilities of acoustical parameters for a certain measurement. The ranges for the different acoustical parameters, are mentioned in Table 3.3.

**Table 3.3:** Parameters, symbols, units, ranges and step size used for the fitting of the models onto the data, ranges are based on findings by Attenborough, Bashir and Taherzadeh [66].

| Parameter[5] | Symbol | Unit | Range | Step size |
|---|---|---|---|---|
| Effective flow resistivity | $\sigma_e$ | kPa s m$^{-2}$ | 10-200 | 2.5 |
| Porosity | $\Omega$ | - | 0.1-1 | 0.05 |
| Structure constant | $c_s$ | - | 1 | - |
| Estimated layer depth | $L_e$ | m | 0-0.2 | 0.02 |

By filling in the different parameter values in the model's impedance function, calculations for the expected level difference at the two microphones over the 1/3-octave bands are performed. The expected $\Delta L$ values for the different 1/3-octave bands and their difference with the measured data is evaluated by Equation 3.8 and 3.9. The lowest value for the RMSE is chosen as best *match*.

[5] Note that not all parameters are used in all models.

In this way an optimal set of parameters can be found by the brute force method. When the lowest error is found, the fitted parameter values together with the error value is displayed. Finally the data is plotted together with the fitted model as seen in Figure 3.14.

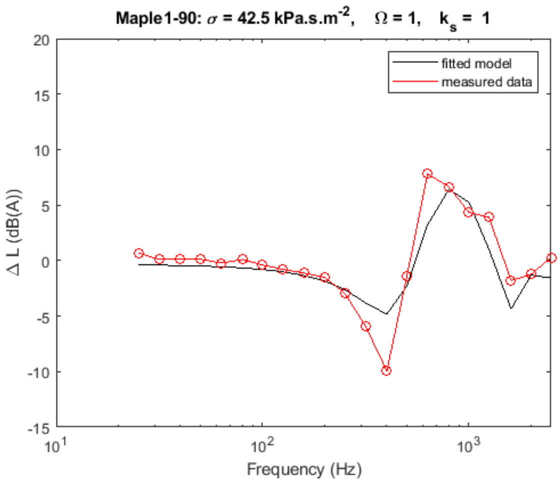



**Figure 3.14:** Measured data and model fit are plotted together on one figure. The Zwikker and Kosten model, Equation 3.7, is used as brute force method for this figure.

### 3.6.1 Statistical tests

Although homoscedasticity is not guaranteed, too few measurements are conducted, some statistical processing was done on the results as well. Significant differences were looked for in the non-acoustical stand characteristics by multiple comparison of the measurements. ANOVA-tables and boxplots are generated of acoustical parameters to see differences between classes, with or without litter and to see the variation in the fitted parameter values. Furthermore linear regression was performed to find relationships between acoustical and non-acoustical stand characteristics. F-stats and p-values were calculated. All were checked on significance at p-value = 0.05.

### 3.6.2 Validation

After the measurement and the brute force parameter determination an extra validation, next to literature checks, is done to check whether the found parameters are realistic. The measurement at the extra height, 700mm, mentioned in Table 3.1, is predicted with the acoustic parameters found for the soil at Nordtest dimensions. If this fits the measured data, it indicates that the soil parameters are probably predicted acceptable. To check the *goodness* of fit, the RMSE error with Equation 3.8 and the NT error Equation 3.9 is calculated, the accumulated error over fitted 1/3-octave bands.

# 4 | Results

The results will be presented in the same order as the research questions, firstly the results of designing a measurement set-up and the MATLAB modelling and secondly the fieldwork results will be presented with some key figures and summarizing tables. For raw data the appendix can be consulted.

## 4.1 Own dimensioning of measurement set-up

Dimensioning the set-up after a theoretical optimization resulted in how the set-up should look like. A maximal value is looked for as this indicates higher differences in the SPL.

In Figure 4.1 (left) the trend for for RMS values is going upwards with increasing distance between the two receivers. This means that when the two microphones are separated further from each other, the difference in signal is higher. For the source, Figure 4.1 (right), two peaks are visible. Around 0.4 m and higher source placement, at 2 m for example there are some very high RMS values (8-11). When the source is low to the ground, but not at ground level, RMS values are high. Also, when the source is high up, differences between the receivers are maximal. Points for these values are not dense on the scatter plot, so are probably outliers. When the effect of height of source and distance between microphones is looked at together, see Figure 4.1(below). It is clear that the effect of distance between two receivers is the more important parameter.

One more parameter needs to be determined, the projected distance between the source and the microphones on the ground. In Figure 4.2 (left) the distance between source and microphones does not seem to have an influence, with increasing distance, no higher RMS values are found. In combination with the distance between microphones, Figure 4.2 (right), the effect of the distance between the microphones is once more clear. Conclusion from this theoretical approach is that placing the two microphones far apart will, theoretically, give higher level difference spectra.

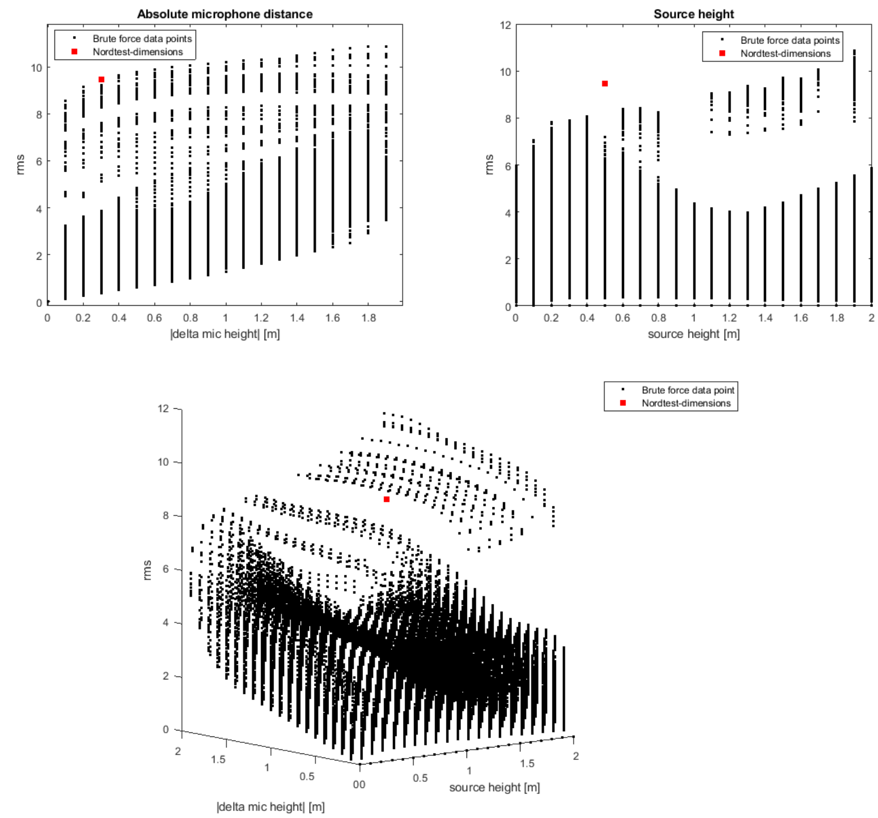



**Figure 4.1:** Difference in height of microphones (left), height of source (right) and the two together (below). On the y-axis (upper figures) or z-axis the value of the RMS is displayed. The x-axis displays the distance between both microphones (left), height of the source (right). The x-axis and y-axis show the two combined (below).

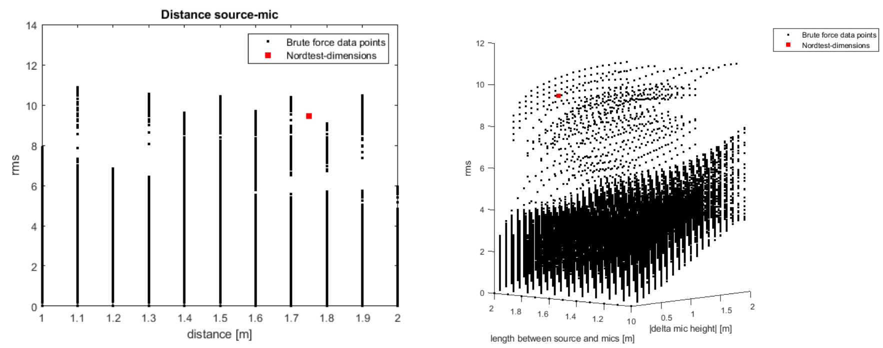



**Figure 4.2:** Distance effect between microphones and source (left) and effect of distance between microphones added (right). On the y-axis (left) or z-axis (right) the value of the RMS is displayed. The x-axis displays the distance between source and microphones (left). The x-axis and y-axis show the distance between source and microphones and the distance between the microphones (right).

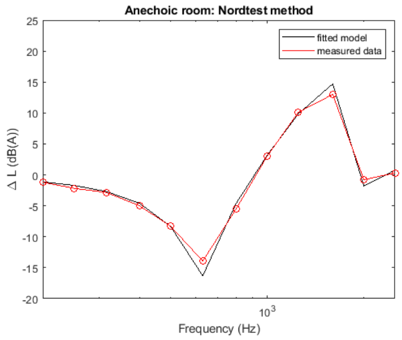



**Figure 4.3:** Data and fit of the model in the anechoic room, RMSE = 0.96 dB $f_c^{-1}$, NT error = 7.99 dB.

## 4.2 Nordtest

Due to the fact that the source is not a perfect point source, the Nordtest method was used [64]. Similar to other set-ups, it was tested on performance. Therefore, the Nordtest set-up was installed in the anechoic room and measurement data was fitted with a hard surface model. For a hard surface model the spherical wave reflection coefficient is assumed 1. In words, sound waves of all frequencies are reflected perfectly by the surface. In Figure 4.3 the result is seen for the frequency spectrum mentioned in Nordtest, 200-2500 Hz [64]. RMSE = 0.96 dB $f_c^{-1}$ and NT error, calculated with Equation 3.9 is only 7.99 dB.

From the anechoic room experiment could be concluded that the set-up performed well. In a next step, some outside measurements were conducted giving good SNR values. Additionally, the model also fitted the outside data accordingly. To compare the Nordtest set-up to own dimensioned set-ups, the RMS value was calculated and plotted with its dimensions onto the figures in section 4.1. This is visualised as a red dot on the plots. It is clear that the Nordtest set-up has a high RMS value, 9.464, but it was never amongst the highest. This is why it did not spark any attention. Furthermore the effect of large distance between the two microphones was this high that it could not be neglected.

## 4.3 Results of the field work

Measurements of acoustical and non-acoustical soil characteristics were performed on three separate days (24 February, 6-7 March 2020). On these days the weather was good enough to organise a field campaign, see Table B.1. Good weather was defined as little wind, preferably below 5 m s $^{-1}$ and no rain. Wind would disturb measurements because microphones would detect the changes in pressure as sound. No rain is mainly to protect the expensive equipment. Both types of measurements are done simultaneously to make sure conditions of acoustical measurements correspond with the correct conditions of soil and litter.

### 4.3.1 Non-acoustical measurement results of fieldwork

The raw data on the non-acoustical results is seen in Appendix B. A summarizing table is made for the most important characteristics. In Table 4.1 the mean values of the 3 litter samples and 4 soil samples per plot is seen. The different measurements are referred to with a key. For example NROak2, is the second sample plot of northern red oak. AmAsh1-90 is the American or white ash measurement done on the first sample plot after turning the set-up 90°.

**Table 4.1:** Mean values of the non-acoustical stand characteristics for the different plots. Mean values are calculated from samples for soil ($N = 4$) and litter ($N = 3$).

| Plot ID | Bulk density (g cm$^{-3}$) | Soil gravimetric moisture content (g g$^{-1}$) | Biomass litter (g) | Litter gravimetric moisture content (g g$^{-1}$) |
|---|---|---|---|---|
| AmAsh1 | 1.09 | 0.36 | 26.43$^a$ | 2.83$^a$ |
| AmAsh2 | 1.20 | 0.54 | 20.79$^a$ | 3.01$^a$ |
| Cherry1 | 1.04 | 0.38 | 25.10$^a$ | 1.50$^b$ |
| Cherry2 | 1.00 | 0.44 | 42.74$^a$ | 2.29$^b$ |
| Lime1 | 1.18 | 0.35$^a$ | 22.06$^a$ | 2.59$^c$ |
| Lime2 | 0.99 | 0.41$^a$ | 33.73$^a$ | 3.62$^c$ |
| Maple1 | 0.98 | 0.40 | 19.49$^a$ | 3.45$^c$ |
| Maple2 | 0.91 | 0.42 | 22.50$^a$ | 3.40$^c$ |
| Beech1 | 0.99 | 0.57$^b$ | 48.42$^b$ | 2.45 |
| Beech2 | 0.98 | 0.46$^b$ | 63.88$^b$ | 2.83 |
| NROak1 | 1.02 | 0.38 | 44.79$^b$ | 2.53$^d$ |
| NROak2 | 0.87 | 0.46 | 63.95$^b$ | 1.84$^d$ |

species mean = mean of plot 1 & 2, significant at p=0.05
$^a$: species mean significantly different from species mean $^b$
$^b$: species mean significantly different from species mean $^a$
$^c$: species mean significantly different from species mean $^b$ and $^d$
$^d$: species mean significantly different from species mean $^c$
no superscript = no significant difference from other species

### Bulk density

Overall the bulk density did not seem to differ a lot between species, the values in the table are the mean of four samples. The minimal value is found at NROak2, with 0.87 g.cm$^{-3}$ and the maximal at AmAsh2 with 1.20 g.cm$^{-3}$. No significant ($p<0.05$) differences between species were found.

### Soil gravimetric moisture content

For soil gravimetric moisture no considerable differences in the mean values. In general there was a lot of variation between measurements at each plot. AmAsh2 for example, ranged from 0.33 to 0.72 g water g$^{-1}$ dry soil. The highest mean value for a species is found for Beech, with 0.51 g water g$^{-1}$ dry soil and Lime the lowest, with 0.38 g water g$^{-1}$ dry soil, these two species are significantly ($p<0.05$) different from each other.

### Biomass litter

Overall the poor litter quality class tends to have the highest litter mass. This is seen for Beech and NROak, with mean values of 56.15 and 54.37 g respectively. Cherry2 seems to be an outlier, 42.74 g, the low value for the other Cherry sample makes the mean value in the range of Lime, an intermediate litter quality class species. Maple has a very low litter biomass with two sample plots of 19.49 and 22.50 g. Poor litter quality differed significantly ($p<0.05$) from the other two litter classes.

### Litter gravimetric moisture content

The litter moisture results between species are the opposite of these for litter biomass. The effect of increasing biomass and decreasing litter gravimetric moisture is almost significant ($p<0.05$) with p-value = 0.07. A lot of significant differences between species were found as is seen in Table 4.1. But the general trend is, the lower the amount of biomass litter, the higher the moist in the present litter.

### Stem density and herbal vegetation cover

**Table 4.2:** Forest stand characterization with number of stems per Fixed Area Plot (FAP) of 100 m², stem number extrapolated to hectare, basal area per ha, dominant herb layer species and secondary species.

| Plot ID | Stems measured (N FAP$^{-1}$) | Stem number (N ha$^{-1}$) | Basal area (m² ha$^{-1}$) | Dominant herb layer vegetation | Secondary species (herb or other) |
|---|---|---|---|---|---|
| AmAsh1 | 7 | 700 | 37.5 | *Urtica dioica* | *Sambucus nigra* |
| AmsAsh2 | 7 | 700 | 44.6 | *Urtica dioica* | *Sambucus nigra* |
| Cherry1 | 5 | 500 | 24.3 | *Rubus spp.* | *Corylus avellana* |
| Cherry2 | 8 | 800 | 33.4 | *Rubus spp.* | *Corylus avellana* |
| Lime1 | 6 | 600 | 40.0 | *Hedera helix* | *Urtica dioica, Dryopteris dilatata, Geum urbanum, Plantago spp.* |
| Lime2 | 6 | 600 | 29.4 | *Hedera helix* | *Urtica dioica, Dryopteris dilatata, Geum urbanum, Plantago spp.* |
| Maple1 | 7 | 700 | 64.1 | *Dryopteris dilatata* | *Hedera helix* |
| Maple2 | 5 | 500 | 32.8 | *Urtica dioica* | *Hedera helix, Sambucus nigra* |
| Beech1 | 3 | 300 | 28.0 | - | |
| Beech2 | 4 | 400 | 78.3 | - | |
| NROak1 | 7 | 700 | 35.8 | *Rubus spp.* | *Crataegus monogyna* |
| NROak2 | 8 | 800 | 54.9 | *Rubus spp.* | *Crataegus monogyna* |

## 4.3.2 Acoustical parameters derived from fieldwork measurements

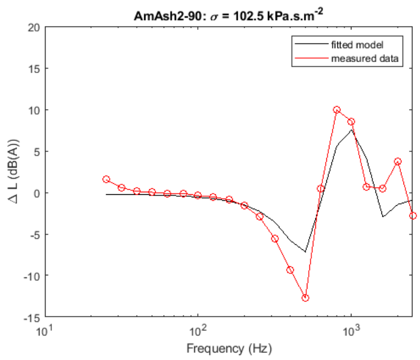
Measurements are performed as described in section 3.5. All eight measurements performed in the six different stands on two different sample plots, this means a total of 96 acoustic measurements. These measurements are then processed step-by-step as is seen in chapter 3, section Data processing.

In Table 4.3 an overview of the different species and models is given together with the errors that indicate the fit of the model: RMSE, Equation 3.8, and Nordtest error, Equation 3.9. Additionally the values for different parameters found by fitting are also displayed. In the last row of each model the mean error of all measurements is given, indicating the overall performance of a used model. In Table 4.4 the fitted parameters on the forest soils with the litter removed are shown, also with RMSE and NT error.

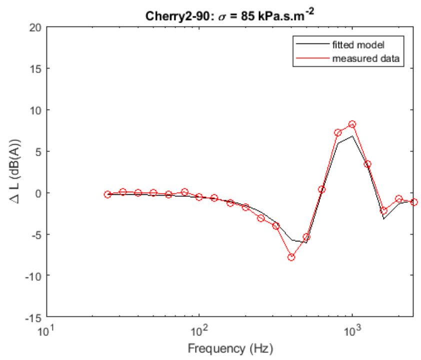
### Delany & Bazley one parameter model

A first step of model fitting was done with the Delany & Bazley one parameter model without hard backing (see Equation 3.1). The Nordtest dimensions are used (see Table 3.1). The only variable fitted in the Delany& Bazley model is effective flow resistivity ($\sigma_e$), this is a flow resistivity value derived from an acoustic measurement. This simple model, normally for rock wool and surprisingly accurate for grassland soil purposes, is more indicative as a first round of modeling. When looking at the results, three things are clear, the performance of the D&B model has a mean RMSE of 1.71 dB $f_c^{-1}$, this is not the worst looking at values of other models. Furthermore some fits are very poor, the fit of AmAsh2-90 has an RMSE value of 2.48 dB $f_c^{-1}$. This is clearly seen in Figure 4.4(a). The model completely misses the peaks starting from 315 Hz and higher. On the other side, are also the values of the already relatively good fitted measurements. For example in Figure 4.4(b) Cherry2-90, were an error of only 0.74 dB $f_c^{-1}$ is found.

Within species there is also some difference for example beech and American/white ash shows homogeneous values for $\sigma_e$. Others have very divergent results, like northern red oak and small-leaved lime, differences between highest and lowest value are 47.5 and 72.5 kPa s m$^{-2}$ respectively. But, as is seen in Table 4.3, these are outliers and other values for these species are more similar. With sycamore maple a very broad range of $\sigma_e$ was found, ranging from 37.5 to 115 kPa s m$^{-2}$. The divergence indicates that a simple mean value is difficult to represent *the* flow resistivity of a species.




**(a)** White ash, *Fraxinus americana* has a rather poor fit, RMSE = 2.48 dB $f_c^{-1}$, NT error = 32.8 dB.

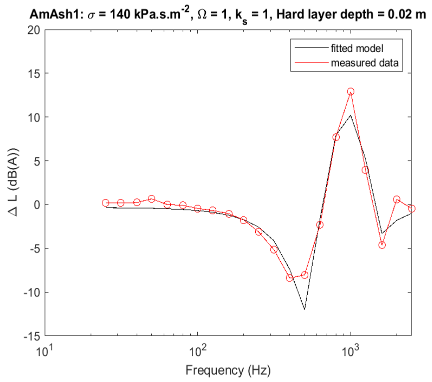



**(b)** Sweet cherry, *Prunus avium* has a rather good fit, RMSE value of 0.74 dB $f_c^{-1}$, NT error = 9.4 dB.

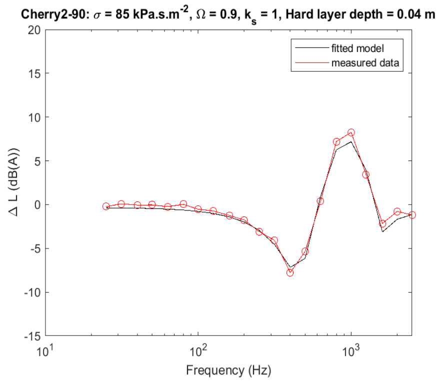
**Figure 4.4:** Examples of Delany and Bazley model fit without rigid backing, Equation 3.1. Plots like this all have the sound pressure level difference ($\Delta L$) on the y-axis and 1/3-octave bands on the x-axis.

**Table 4.3:** Table with all the parameter values for the different models with RMSE as calculated with Equation 3.8 and NT error as calculated with Equation 3.9.

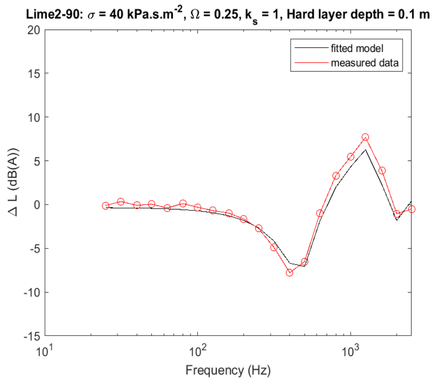
| Plot ID | Delany and Bazley | | | Delany and Bazley rigid backing | | | | Zwikker and Kosten | | | | Zwikker and Kosten rigid backing | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Effective flow resistivity (kPa s m$^{-2}$) | RMSE (dB $f_c^{-1}$) | NT Error (dB) | Effective flow resistivity (kPa s m$^{-2}$) | Effective layer depth (m) | RMSE (dB $f_c^{-1}$) | NT Error (dB) | Effective flow resistivity kPa s m$^{-2}$ | Effective porosity - | RMSE (dB $f_c^{-1}$) | NT Error (dB) | Effective flow resistivity kPa s m$^{-2}$ | Effective porosity - | Effective layer depth (m) | RMSE (dB $f_c^{-1}$) | NT Error (dB) |
| AmAsh1 | 120 | 1.56 | 18.4 | 10 | 0.02 | 2.45 | 30.4 | 110 | 1 | 1.53 | 19.6 | 140 | 1 | 0.02 | 1.31 | 16.1 |
| AmAsh1-90 | 117.5 | 1.44 | 17.7 | 10 | 0.02 | 2.52 | 30.8 | 110 | 1 | 1.49 | 18.9 | 100 | 0.75 | 0.04 | 1.46 | 17.7 |
| AmAsh2 | 102.5 | 1.95 | 27.2 | 10 | 0.02 | 2.21 | 28.6 | 92.5 | 1 | 1.98 | 19.8 | 120 | 1 | 0.02 | 1.54 | 19.7 |
| AmAsh2-90 | 102.5 | 2.48 | 32.8 | 10 | 0.02 | 2.58 | 29.8 | 92.5 | 1 | 2.57 | 33.0 | 110 | 1 | 0.02 | 1.97 | 22.5 |
| Cherry1 | 67.5 | 1.76 | 20.5 | 20 | 0.02 | 1.71 | 21.6 | 57.5 | 1 | 1.76 | 19.6 | 55 | 0.85 | 0.04 | 1.19 | 16.3 |
| Cherry1-90 | 105 | 1.55 | 18.8 | 177.5 | 0.02 | 2.18 | 30.1 | 45 | 0.45 | 1.43 | 17.0 | 50 | 0.45 | 0.08 | 1.31 | 14.1 |
| Cherry2 | 85 | 1.18 | 14.0 | 100 | 0.02 | 1.92 | 24.4 | 45 | 0.55 | 1.13 | 12.9 | 60 | 0.6 | 0.06 | 1.1 | 12.3 |
| Cherry2-90 | 85 | 0.74 | 9.4 | 17.5 | 0.02 | 1.66 | 19.8 | 77.5 | 1 | 0.71 | 8.2 | 85 | 0.9 | 0.04 | 0.51 | 7.0 |
| Lime1 | 170 | 1.32 | 17.8 | 10 | 0.02 | 3.32 | 35.9 | 170 | 1 | 1.31 | 17.5 | 95 | 0.45 | 0.04 | 1.15 | 13.6 |
| Lime1-90 | 170 | 1.43 | 18.7 | 10 | 0.02 | 3.36 | 36.2 | 172.5 | 1 | 1.42 | 18.6 | 95 | 0.45 | 0.04 | 1.19 | 14.3 |
| Lime2 | 97.5 | 1.93 | 18.9 | 122.5 | 0.02 | 2.49 | 32.2 | 45 | 0.5 | 1.97 | 20.4 | 50 | 0.4 | 0.06 | 1.88 | 17.5 |
| Lime2-90 | 137.5 | 1.83 | 21.9 | 200 | 0.02 | 2.08 | 27.4 | 3 0 | 0.25 | 1.23 | 15.2 | 40 | 0.25 | 0.1 | 0.75 | 10.2 |
| Maple1 | 37.5 | 1.54 | 20.4 | 52.5 | 0.02 | 1.77 | 22.6 | 25 | 0.85 | 1.51 | 19.2 | 25 | 0.6 | 0.08 | 0.84 | 11.1 |
| Maple1-90 | 52.5 | 1.89 | 21.8 | 32.5 | 0.02 | 1.93 | 23.3 | 40 | 0.95 | 1.86 | 21.4 | 30 | 0.6 | 0.06 | 0.97 | 9.7 |
| Maple2 | 115 | 1.26 | 15.1 | 17.5 | 0.02 | 2.56 | 31.3 | 110 | 1 | 1.22 | 15.3 | 80 | 0.7 | 0.06 | 1.23 | 14.0 |
| Maple2-90 | 82.5 | 1.67 | 17.5 | 15 | 0.02 | 1.87 | 21.5 | 70 | 0.95 | 1.72 | 18.5 | 35 | 0.4 | 0.06 | 0.97 | 12.2 |
| Beech1 | 55 | 2.51 | 31.0 | 47.5 | 0.02 | 2.54 | 30.5 | 27.5 | 0.6 | 2.53 | 31.3 | 25 | 0.4 | 0.08 | 1.24 | 16.1 |
| Beech1-90 | 67.5 | 2.20 | 29.1 | 52.5 | 0.02 | 2.42 | 29.1 | 30 | 0.5 | 2.19 | 27.2 | 30 | 0.35 | 0.08 | 1.39 | 16.8 |
| Beech2 | 50 | 2.01 | 28.5 | 137.5 | 0.02 | 1.75 | 22.7 | 15 | 0.35 | 1.54 | 18.5 | 20 | 0.35 | 0.12 | 1.1 | 12.3 |
| Beech2-90 | 40 | 2.23 | 27.3 | 82.5 | 0.02 | 2.26 | 28.3 | 17.5 | 0.5 | 2.15 | 26.3 | 15 | 0.35 | 0.1 | 0.87 | 9.6 |
| NROak1 | 107.5 | 2.01 | 27.3 | 200 | 0.02 | 1.9 | 23.4 | 27.5 | 0.3 | 1.41 | 18.6 | 30 | 0.25 | 0.12 | 0.91 | 10.7 |
| NROak1-90 | 97.5 | 1.65 | 21.6 | 190 | 0.02 | 1.9 | 23.8 | 32.5 | 0.35 | 1.31 | 17.4 | 45 | 0.35 | 0.08 | 1.15 | 14.1 |
| NROak2 | 92.5 | 1.42 | 16.3 | 115 | 0.02 | 2.1 | 26.3 | 47.5 | 0.55 | 1.4 | 16.6 | 45 | 0.55 | 0.12 | 1.39 | 16.2 |
| NROak2-90 | 60 | 1.40 | 15.7 | 55 | 0.02 | 1.43 | 17.7 | 30 | 0.6 | 1.43 | 15.9 | 30 | 0.6 | 0.16 | 1.4 | 14.9 |
| Mean | | 1.71 | 21.2 | | | 2.2 | 27.0 | | | 1.6 | 19.5 | | | | 1.2 | 14.1 |



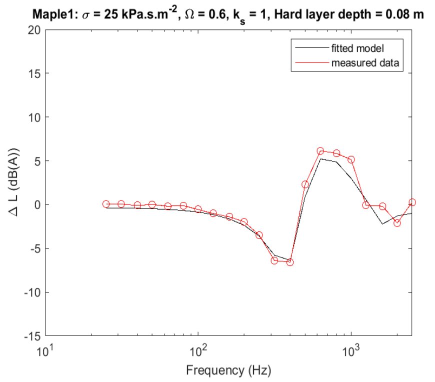

**(a)** White ash, RMSE = 1.31 dB $f_c^{-1}$



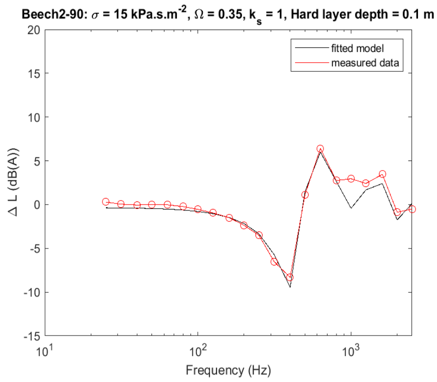

**(b)** Sweet cherry, RMSE = 0.51 dB $f_c^{-1}$



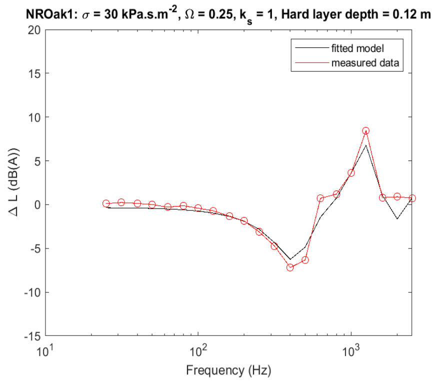

**(c)** Small-leaved lime, RMSE = 0.75 dB $f_c^{-1}$




**(d)** Sycamore maple, RMSE = 0.84 dB $f_c^{-1}$




**(e)** Beech, RMSE = 0.87 dB $f_c^{-1}$




**(f)** Northern red oak, RMSE = 0.91 dB $f_c^{-1}$

**Figure 4.5:** Representation of the fitting of the Zwikker & Kosten model with hard backing (Equation 3.2 and 3.7) onto the data. RMSE values for fitting are also given (Equation 3.8)

**Table 4.4:** Results of the fitting of the parameters on the data of the soil layers after the litter was removed. Data is fitted with the Z&K model with rigid backing.

| Plot ID | Effective flow resistivity (kPa.s.m$^{-2}$) | Effective porosity - | Effective layer depth (m) | RMSE (dB $f_c^{-1}$) | NT Error (dB) |
|---|---|---|---|---|---|
| AmAsh1 | 70 | 0.6 | 0.04 | 1.37 | 17.9 |
| AmAsh1-90 | 130 | 0.7 | 0.02 | 1.54 | 18.5 |
| AmAsh2 | 85 | 0.6 | 0.04 | 1.53 | 21.2 |
| AmAsh2-90 | 35 | 0.25 | 0.06 | 1.43 | 16.9 |
| Cherry1 | 45 | 0.5 | 0.06 | 1.35 | 17.9 |
| Cherry1-90 | 55 | 0.4 | 0.08 | 1.46 | 16.8 |
| Cherry2 | 110 | 0.7 | 0.04 | 1.14 | 13.8 |
| Cherry2-90 | 95 | 0.6 | 0.04 | 0.62 | 7.0 |
| Lime1 | 170 | 0.9 | 0.02 | 1.31 | 15.7 |
| Lime1-90 | 200 | 0.9 | 0.02 | 1.05 | 13.2 |
| Lime2 | 55 | 0.25 | 0.08 | 0.48 | 4.8 |
| Lime2-90 | 55 | 0.2 | 0.08 | 0.65 | 8.1 |
| Maple1 | 30 | 0.45 | 0.08 | 1.1 | 11.7 |
| Maple1-90 | 40 | 0.5 | 0.06 | 0.88 | 9.7 |
| Maple2 | 95 | 0.8 | 0.04 | 1.1 | 12.0 |
| Maple2-90 | 70 | 0.55 | 0.04 | 0.74 | 8.9 |
| Beech1 | 145 | 0.9 | 0.02 | 0.16 | 20.2 |
| Beech1-90 | 180 | 0.75 | 0.02 | 1.31 | 16.6 |
| Beech2 | 40 | 0.5 | 0.06 | 1.39 | 17.8 |
| Beech2-90 | 60 | 0.65 | 0.04 | 0.98 | 11.4 |
| NROak1 | 180 | 1 | 0.02 | 1.38 | 16.9 |
| NROak1-90 | 105 | 0.45 | 0.06 | 0.9 | 10.4 |
| NROak2 | 75 | 0.4 | 0.08 | 0.88 | 9.5 |
| NROak2-90 | 60 | 0.7 | 0.1 | 1.22 | 12.7 |
| Mean | | | | 1.08 | 13.7 |

#### Delany & Bazley one parameter model with rigid backing

In a second step, a hard backing is implemented in the code by adding an extra variable $L_e$, see Equation 3.2. $L_e$ is the best estimated dept of the rigid or acoustically hard layer. The presence of a rigid layer has a significant influence on the reflecting behaviour of sound waves. This hard layer was seen by Martens et al. and is expected to improve the previous D&B fit. Conversely, looking at the mean value of the error it does not perform well, RMSE = 2.2 dB $f_c^{-1}$. Also all the rigid layers were found at a depth of 0.02m, despite including the parameter in the brute force method. The highest RMSE values of the table are also seen for this type of modeling. For Lime1 and Lime1-90 values of 3.32 and 3.36 dB $f_c^{-1}$ are found respectively. Furthermore within this species, large heterogeneity was found for lime, between 10 and 200 kPa s m$^{-2}$. And no NT error values were found under the threshold value of 15 dB, Cherry2-90 came closest with 19.6 dB.

#### Zwikker & Kosten phenomenological model

In a third round, the physically more correct Zwikker & Kosten phenomenological model with 3 parameters is implemented. The estimated parameters are effective flow resistivity $\sigma_e$, structure constant $c_s$ and porosity $\Omega$. As mentioned before, the structure coefficient, $c_s$, is of minor influence and kept one for all fitting (for this model and Z&K with rigid backing). The other parameters have been estimated by the brute force method. The overall result is slightly better than D&B with a mean RMSE = 1.6 dB $f_c^{-1}$. This is quite good, but not a big improvement. The same 'extremes' pop up for good and poor fitting, respectively Cherry2-90 and AmAsh2-90.

### Zwikker & Kosten phenomenological model with rigid backing

As a final step in fitting, the Z&K model is extended with a rigid backing. This led to an overall better performance. The mean RMSE over all the plots is 1.2 dB $f_c^{-1}$. And for the NT error, 14.1 dB that is ≈ 5 dB better than Z&K without rigid backing. This means that on average the threshold value set by Nordtest of 15 dB was met. In Figure 4.5 the best fits/smallest errors are illustrated for every species, together with the determined variables. It is clear that all the measurements show a clear *ground dip*. This dip can differ in 1/3-octave band and in amplitude. For white ash the *dip* is much deeper, down to -11 dB for the model, and a very steep and high top at 1000 Hz. While for other species beech, northern red oak and maple, the dip does not reach -10 dB, but -8.13, -7.19 and -6.576 dB respectively, but these do not have such a pronounced top at 1000 Hz. The occurrence of a dip at a specific 1/3-octave band does not differ that much between the species and is mostly 400 Hz, 500 Hz or something in between like the flattened *dip* for sycamore maple, white ash and northern red oak. Overall, the dip or amplitude in dip did not seem to differ that much between species.

### Statistical analysis on acoustical parameters

In Figure 4.6 the distribution of the acoustical parameters is seen in boxplots. One-way analysis of variance (ANOVA) is performed on the species effect. A summarizing table on the species effect on derived acoustical parameters, before litter layer removal, is seen in Table 4.5. It is clear that species have a strongly significant effect, p$\ll 0.001$, for all three estimated parameters. This means that differences are present between species for the acoustical properties. This also implies that certain species have more desired characteristics than others. Because the litter layer is still present, it could be that this is the driver for the differences between species.

Furthermore, two-way ANOVA is performed. The column is the effect between litter layer quality classes and the row effect the presence or absence of the litter layer. Litter layer classes are chosen to make more general trends clear. The null hypothesis for row effect is that the presence of litter does not influence the parameters. The null hypothesis of the column effect is that all means are equal $\mu_{Good} = \mu_{Intermediate} = \mu_{Poor}$. A summary of the statistics is found in Table 4.6.

In the two-way ANOVA, Table 4.6, the interaction effect of species and removal of the litter is significant for all three acoustical parameters. This means that the litter layer is important in the difference between species. Which confirms the suggestion made with the one-way ANOVA. Further in the two-way ANOVA, it is seen that for rigid layer depth the main row and column effect is also significant between species. This is visually confirmed in Figure 4.6. The downward trend of depth of the rigid layer remains present after litter layer removal. For the other acoustical parameters ($\sigma_e, \Omega$) the significant interaction effect is also clearly visible in Figure 4.6. The changes in values before and after litter layer removal are obvious. But, for these parameters the trend before and after removal is not as clear as for the rigid layer depth and makes the species rather uniform. That is why the main effects are not significant.

**Table 4.5:** One-way ANOVA performed on the acoustic parameter data to look for the main effects between species with litter layer present. F-stat, p-value and significance level are given.

| Parameter | F(5, 18) | p-value | Sign? |
|---|---|---|---|
| Flow resistivity (kPa s $m^{-2}$) | 12.6 | $\ll$0.001 | *** |
| Porosity (-) | 9.7 | 0.0001 | *** |
| Layer depth (m) | 9.43 | 0.0002 | *** |

*** = p<0.001

**Table 4.6:** Two way ANOVA performed on the acoustic parameter data to look for the main effects. The column effect is between litter quality classes(good, intermediate and poor) and the row effect is the presence of the litter layer (present or absent). F-stat, p-value and significance level are also given.

| Parameter | Effect | df | F(df, 42) | p-value | Sign? |
|---|---|---|---|---|---|
| Flow resistivity | Litter quality class | 2 | 0.61 | 0.548 | ns |
| (kPa s $m^{-2}$) | Litter presence | 1 | 3.14 | 0.084 | ns |
| | Interaction | 2 | 4.84 | 0.0129 | * |
| Porosity | Litter quality class | 2 | 3.16 | 0.053 | ns |
| (-) | Litter presence | 1 | 0.23 | 0.64 | ns |
| | Interaction | 2 | 7.9 | 0.0012 | ** |
| Layer depth | Litter quality class | 2 | 14.02 | 0.009 | ** |
| (m) | Litter presence | 1 | 8.06 | 0.0069 | ** |
| | Interaction | 2 | 7.6 | 0.0015 | ** |

ns = p >0.05, * = p<0.05, ** = p<0.01

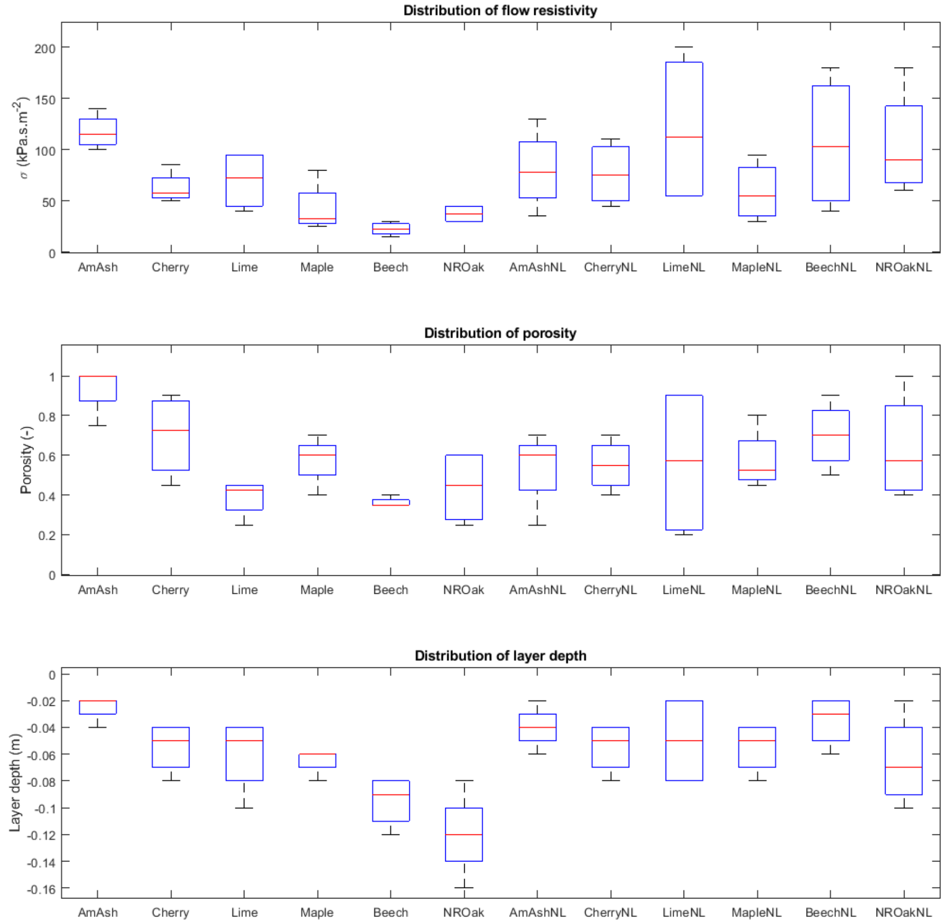



**Figure 4.6:** Distribution of the different fitted acoustic parameters on data with and without litter (e.g. CherryNL = Cherry No Litter), for all boxplots $N = 4$. The species paired up in a litter quality classes are displayed next to each other. From left to right: good, intermediate and poor degrading litter quality.

### Validation

To validate the parameters found by the Z&K rigid backing model, the SPL spectra with the upper microphone at 700mm, see Table 3.1, are predicted. Errors of the fit of the prediction to the data are shown in Table 4.7. Rather low RMSE values and a mean NT error over all the measurements of 18.27 dB was found, this is quite accurate regarding the mean values of the error found at other models in Table 4.3.

**Table 4.7:** Validation of fitted parameters by sample plots and RMSE (Equation 3.8) and NT error (Equation 3.9) of the predicted parameter curve and the collected data for the microphone at 700mm, see Table 3.1.

| Plot ID | RMSE | NT Error (dB) | Plot ID | RMSE | NT Error (dB) | Plot ID | RMSE | NT Error (dB) |
|---|---|---|---|---|---|---|---|---|
| AmAsh1 | 1.36 | 16.8 | Lime1 | 1.07 | 12.1 | Beech1 | 1.49 | 16.7 |
| AmAsh1-90 | 1.42 | 17.7 | Lime1-90 | 1.13 | 12.6 | Beech1-90 | 2.14 | 30.2 |
| AmAsh2 | 1.66 | 21.6 | Lime2 | 2.39 | 32.5 | Beech2 | 0.99 | 11.9 |
| AmAsh2-90 | 2.00 | 22.3 | Lime2-90 | 1.46 | 16.6 | Beech2-90 | 1.03 | 12.8 |
| Cherry1 | 1.58 | 17.8 | Maple1 | 2.53 | 32.5 | NROak1 | 1.47 | 18.4 |
| Cherry1-90 | 1.24 | 15.3 | Maple1-90 | 2.05 | 23.8 | NRoak1-90 | 1.52 | 19.5 |
| Cherry2 | 1.36 | 17.0 | Maple2 | 1.08 | 11.6 | NROak2 | 1.33 | 11.7 |
| Cherry2-90 | 1.61 | 18.6 | Maple2-90 | 1.14 | 12.3 | NROak2-90 | 1.92 | 15.6 |

## 4.4 Acoustical and non-acoustical data relationships

The first graph, Figure 4.7, shows the relationship between biomass and flow resistivity. In the right graph, the negative correlation is seen. The more litter, the lower the flow resistivity. The confidence bounds of this relationship are rather close to the fit. The fit is significant, $F(1,22) = 9.25$, p-value $= 0.006$, the $R^2$ is 0.296.

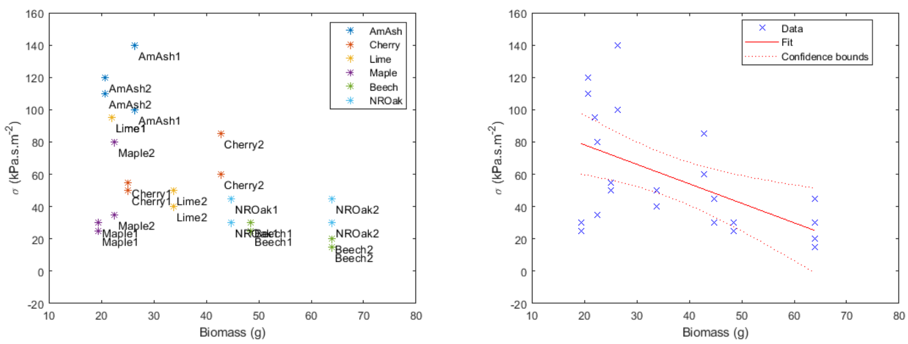



**Figure 4.7:** Data points with labels of species (left), with on the y-axis the flow resistivity and on the x-axis the biomass of the litter layer. Linear regression and confidence intervals of the data (right).

The second graph, Figure 4.8, displays the effect of bulk density of the soil on the flow resistivity. Here an almost significant, $F(1,22) = 4.03$, $p = 0.057$, positive correlation is seen between the flow resistivity and the bulk density of the soil. The higher the bulk density, the higher the effective flow resistivity values. The $R^2$ has a value of 0.155 so here not a lot of variance in the flow resistivity is explained by the model.

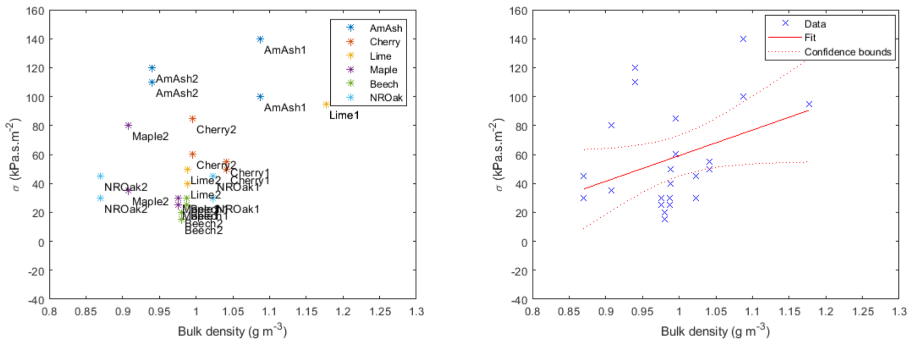



**Figure 4.8:** Data, with litter layer, points with labels of species (left), with on the y-axis the flow resistivity and on the x-axis the bulk density of the soil. Linear regression and confidence intervals of the data (right).

When these two effects are combined in a multiple linear regression model:

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \epsilon \tag{4.1}$$

With, y the flow resistivity, $X_1$ the biomass and $X_2$ the bulk density of the soil. This model accounts for 33.9% of the variance in the effective flow resistivity values. The model has a p-value = 0.013 and F(2,21) = 5.38. Furthermore, the lack-of-fit confirmed that the model needed extra parameters or more data, F(9,21) = 8.86, p = 0.0004.

The last graph, Figure 4.9, is mostly to control the fitted parameters by the acoustical models. This shows the relationship between the depth of the rigid layer and the amount of biomass litter. The y-axis is shown with negative values, 0 is ground level or top of the litter layer. It is expected that the deeper the layer, lower values are seen at species with higher biomass values e.g. beech, northern red oak. This is what is seen in the graph. The lower the rigid layer is found in the soil the higher the biomass. With a p $\ll$0.001, F(1,22) = 31.1 and an $R^2$ value of 0.586, biomass has an influence on the rigid layer depth. When now a multiple regression is done, as in Equation 4.1 with layer depth and biomass (see Figure 4.7) $X_1$ and $X_2$, respectively. The model is strongly significant, F(2.21) = 16.7, p$\ll$0.001 and $R^2$ = 0.614. The lack of fit for this model was F(17,21) = 2.21, p = 0.231, this means that the model is a good predictor of the $\sigma_e$. Although both layer depth and flow resisitivity are fitted by the same model, this strong relation between litter and flow resistivity needs to be pointed out.

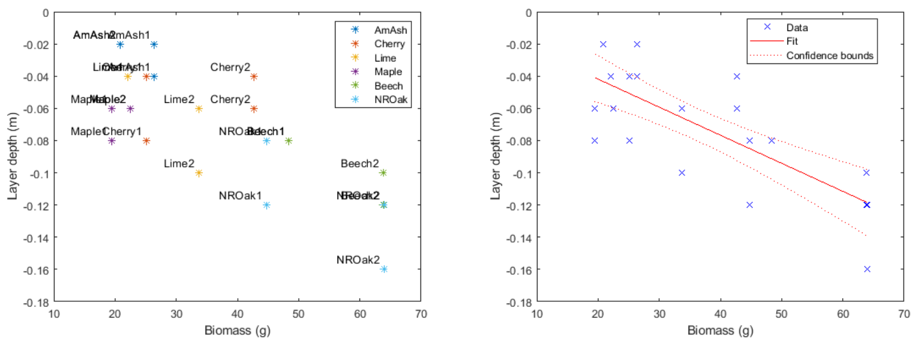



**Figure 4.9:** Data points with labels of species (left), with on the y-axis the rigid layer depth below the surface (=0 m) and on the x-axis the biomass of the litter layer. Linear regression and confidence intervals of the data (right).

Finally moisture content levels of litter and soil were compared to $\sigma_e$ levels. This gave non-significant results. Higher levels of soil moisture were linked to lower effective flow resistivities. This was a non significant result ($F(1,22) = 0.62$, $p = 0.439$). Furthermore litter moisture level and $\sigma_e$ were unrelated, an almost flat linear regression was found ($F(1,22) = 0.0389$, $p = 0.845$). This means that flow resisitivity had almost no relationship with litter moisture. When litter biomass is linked with soil moisture a non-significant positive relation is found. More litter means that the soil is more moist, $F(1,22) = 3.02$, $p = 0.0963$.

# 5 | Discussion

## 5.1 Own dimensioning of measurement set-up

The first part is an exploratory study of measurement set-ups for soil impedance characteristics. The validation of the set-up before actual field work is important to fully understand the technique and to make valuable conclusions.

The brute force method dimensioning of the set-up resulted in the following dimensions. The two microphones/receivers were placed far from each other, 1.9 m, to maximize the difference in sound pressure level. The source was placed more near ground (0.3 m) as is seen in section 4.1 gives the highest values for the RMS. The microphones were placed $\sim$1.5 m from the source, to avoid interactions in the near field.

Although this way of thinking and the theoretical background of the measurements seemed correct, physically based on the Z&K model, problems occurred in the anechoic room. When data gathered from measurements with the set-up were fitted with a model, poor results were found. The main issue was that models failed to fit the *dip* in the correct 1/3-octave band. To make sure no early conclusions were drawn some repetitions and changes in dimensions were performed. Furthermore also a comparative analysis of different soil types is done to see if the set-up would reveal differences between three soil types: grassland, forest floor and asphalt. All test measurements ended up in poor fits of the model to the data. These findings led to the limitation (red block) seen in Figure 3.1.

A possible explanation, as mentioned before, could be a practical limitation of the source. The model assumes that the source is a perfect point source. A perfect point source emits exactly the same acoustic energy in all directions. But, the loudspeaker used in the set-up is not a perfect point source, thus cannot emit the same amount of sound energy in all directions. Because the microphones are placed far from each other, the incoming direct energy is different and the model does not hold anymore. The sound pressure level difference detected at the receivers is thereby not solely induced by the ground effect.

### Nordtest

These findings led to using the Nordtest method [64], in the Nordtest-method the two receivers are more or less in the same directional path of the sound with only a 0.3 m difference between receivers. This results in direct paths of 1.775 m (for the lower receiver) and 1.75 m (for the upper receiver) this was 1.53 m and 2.19 m respectively for the set-up as dimensioned by the brute force results. A maximal difference in $\Delta L$ was thus not the right parameter for optimising the dimensions.

## 5.2 Non-acoustical fieldwork measurements

### Litter sampling

Non-acoustical measurements are collected to explain trends in acoustical parameters between species. In Table 4.1, mainly the differences in litter data stand out, almost no significant differences were found between the soil parameters. Multiple comparison tests pointed out significant litter value differences for several species. Biomass values of litter quality class good and intermediate are all significantly lower than the values of poor litter quality. Th observed values for biomass seem to be realistic for the good and intermediate quality class but for poor degrading litter, an average value of 55.5 g for beech seems to be low compared to what Vesterdal et al. found [97]. The values found by Vesterdal et al. belonged to an experiment established in 1973 so values in Mortagne should be more or less comparable. The significant differences between the group maple, ash, lime and the group common oak (*Quercus rubra*) and beech is something Vesterdal et al. also found. Nutrient composition and acidification of the litter can be an explanation for the differences in biomass. Characteristic for northern red oak and beech are higher pH and low $Ca^{2+}$ soil values that resulted from low quality litter [76, 87, 97]. Furthermore the earthworm effect is something that also can be important for differences in litter composition and weight. Species of litter quality class good and intermediate are associated with higher earthworm, *Lumbricidae*, densities. Earthworms speed up the turnover rate of litter significantly [98, 99]. The higher values for Cherry2 and Lime1 cannot be declared and are described to human induced litter sample contamination with non-foliar litter material like branches and moss.

### Soil sampling

Soil measurements had in general lower degrees of variance within and between species. The two sample plots seemed to differ less in the soil parameters from each other then for the biomass and litter moisture content. When looking at the values for the soil parameters Lime1 stands out with a high value, this could be because sample plots of small-leaved lime lie in another soil type (Adp in stead of Ada). Cherry also lies in this other soil type but no significant difference was found from other stands that lie in the Ada soil type. The order of results seems to match values found in literature [97, 100]. And low variance between species is also seen by Vesterdal et al. [97].

**Stem density and herbal vegetation cover**

Results of the description of the stands will not be discussed thoroughly but do give an indication on how the sample plots were selected. The idea was to have low tree density/basal area. Results are seen in Table 4.2, the stem numbers are very low, especially when compared to numbers in the forest management plan [73], with on average 1187 trees $ha^{-1}$. The forest management plan dates from 2005, so the order of stem numbers differs a lot. It is known that forests loose a lot of stems between 35 and 50 years [87]. But the low stem number indicate that picking low density plots, to diminish scatter effects from trunks, was performed quite well. Basal area values are high, this is probably because the trees have more area per individual and the measured trees are bigger then in higher density plots. When these numbers, N and basal area, are extrapolated to hectares it gives probably a distorted view of the situation in Mortagne.

Herb layer abundance was in general rather low, the short time after winter (March) could explain this. Also no plot showed very high abundances because they were selected on that criterion. Concluding from low herb layer and tree density numbers, it can be expected that the main effects in the acoustic measurements will be from the ground.

## 5.3 Acoustical measurements

### 5.3.1 Model evaluation

The different models used in the brute fore method were all technically reviewed in subsection 4.3.2. It is obvious that step-by-step adding parameters to the model helped improving the fitting and values for RMSE and NT error decreased. In the last line of Table 4.3 the improvement is clearly visible. The Z&K with a rigid backing gave the best results. What was expected, and suggested and researched by Attenborough [66, 101]. Forest floors can be seen as a porous layer on a rigid layer (mineral soil), see Figure 2.6. To check the model's goodness-of-fit, the Nordtest error can be compared to other studies that also use this value as a proxy for fitting. A model comparing study by Attenborough, Bashir and Taherzadeh used Nordtest dimensions and calculated the error, proposed by Nordtest [64] (see Equation 3.9), for the different ground impedance models. In Table 4.3 the average NT error for all plots is 14.1 dB, this is under the threshold value proposed by Nordtest for validity. The threshold value is also obtained by Attenborough, Bashir and Taherzadeh in 2 out of 3 beech stands with the phenomenological model with rigid backing, the same as Z&K with rigid backing. In this study, the D&B one parameter models also struggled to fit forest data properly. The D&B model is originally designed for rock-wool and surprisingly performs well for grass-covered soils. This could explain the rather difficult fitting on forest floor data.

A noteworthy measurement is Cherry2-90, that has a very low error value throughout the table. No conclusive answer can be given for this but it might be that for this type of ground, the used models are appropriate. The shape of the data, as is seen in Figure 4.5(b), is continuous without sudden jumps or peaks, opposed to Figure 4.5(f) and 4.5(e). For these measurements, more parameter models, four or more, could improve fitting.

#### Validation

The validation step of predicting the level difference spectra for a set-up with higher microphone seemed to work remarkably well, see Table 4.7. Unsatisfactory results (NT error >30 dB) were only found for 3 measurements. On the other hand, the criterion of <15 dB was only met 7 times. The validation reveals that the ground reacts in more or less the same way as with the set-up in Nordtest dimensions. Which is not abnormal, because the same model is used. But, the spectral difference curve is dependant on the reciprocal position of the source and receivers [60]. Thus when the spectral difference curve can be predicted, it could indicate that the acoustical ground parameters are quite properly fitted.

### 5.3.2 Determined acoustical parameters from fieldwork

#### Literature check

Fitted parameters were also compared to literature. The mean value for beech, 22.5 kPa s $m^{-2}$, is close to the mean value found by Attenborough, Bashir and Taherzadeh for beech stands with the phenomenological layer model [66], 20.4 kPa s $m^{-2}$. For porosity similar values were found as well, in the range of 0.35-0.4 and in the paper 0.41-0.5. Furthermore the layer depth is between 0.08 and 0.1 m in the paper, the values for the studied beech stands in Mortagne are 0.08-0.12m so another indication that the results are realistic. Also the mean values for good and intermediate degrading litter, 90 and 56.25 kPa s $m^{-2}$, respectively, lie within the range that is accepted for forest soils 9-200 kPa s $m^{-2}$. But in general not that much literature or data is available to compare acoustical properties of deciduous species.

In the used model, values are specific for set-up dimensions, but it can be assumed that these remain constant on the metal frame. With this assumption, observations for the ground dip variance in frequency band and amplitude, see

Figure 4.5, can be related to the acoustical properties of the soil. Although mitigation effects found by the modeling of the short-range propagation may not be correct in absolute size, due to specific geometry, they can be used to compare the species and groups (good, intermediate and poor degrading litter). In general the dip is seen at more or less the same 1/3-octave bands, 400-500 Hz. What is expected of ground effects and found in literature [58].

#### Trends and statistical analysis on determined acoustical parameters

The results of the comparison between species and classes are more or less the same. In the distribution of the parameters over the species, seen in Figure 4.6, the gradients are clearly visible. In general the trend between species and classes is downward. The flow resistivity is in general highest for the good degrading species. This means that these species show more traits of harder soil, the higher the flow resistivity the higher the soil reacts as a hard surface [23]. The lower, the more the soil reacts as an absorber, but a perfect absorber is also not desired while this inhibits the desired destructive interference reactions. This difference could be described to the presence of a thick litter pack with for example northern red oak and beech [97]. The interaction effect for flow resistivity, Table 4.6, between litter classes and litter layer presence is significant, meaning that for some species the presence of the litter layer is influencing the value of $\sigma_e$. This is clearly the case for NROak and Beech, as is seen in Figure 4.6. Results are contrary to what Aylor suggested, that a loose litter layer does not affect the ground effect [33]. Difference with and without litter layer was also performed by Reethof, Frank and McDaniel and resulted in absorption coefficient differences of maximally 0.25 for certain octave bands [58].

Porosity is difficult to interpret, seems to be very variable and only a slight downward trend is seen in Figure 4.6. With lower porosity for poorly degrading species. Porosity is a very important parameter for sound absorbing materials [58]. Also, a significant interaction effect is found for the litter quality class and litter presence, Table 4.6. This means that for some species the removal of the litter layer changed the porosity. This is clearly visible in Figure 4.6, the mean values for porosity after litter removal were almost all equal. It was expected that removal would influence values of species with a lot of litter but not the species with almost no litter. This is not explicable. The only possibility might be that raking away the litter layer would have compacted the soil. Furthermore it has to be pointed out that porosity levels for Cherry and AmAsh were very high in the initial measurement before raking.

Layer depth has a clear downward trend for species with slower conversion rates of litter. Thus the rigid layer for beech and northern red oak lies deeper in the soil, important to consider is that 0 is ground level. This trend could be explained by the thicker pack of leaves [97]. But looking at the layer depth without litter the same trend is seen, although less strong. A possible explanation could be that the effects of the species go deeper than the loose litter layer only. A suggestion is that there is a thicker transition layer from litter to mineral soil present. Because of more biomass, it is this layer of semi-composed material that causes the persistent rigid layer effect seen in Figure 4.6. Nevertheless the acoustical behaviour seen with litter is also the effect for noise mitigation in a real life situation. No forest will ever have all its litter removed, thus the differences between species with litter are still the most important. These effects are also seen in the two way ANOVA performed on the litter quality classes and will be discussed in the next paragraph.

The species effect is clear for all three parameters. In a one-way ANOVA, Table 4.5, the species effect is strongly significant, $p<0.001$, for all three parameters, in this analysis the litter layer was still present. This indicates that species do differ acoustically. When taking litter into account as well, in the two-way ANOVA, see Table 4.6. It is clear that the litter layer presence is important for the acoustic properties. The interaction term was significant for all three parameters. This means that litter layer is an important factor in determining the differences between species. And in the layer depth, it is clear that removing the litter layer was significant for all effects. With the fact that the species do differ strongly significant when the litter layer is removed and this effect is lost when the litter layer removal is included in the analysis, it can be concluded that the litter layer is one of the most important factors for the ground effect.

## 5.4 How are forest and acoustics now linked?

### Flow resisitivity and non-acoustical parameters

In Figure 4.7 a significant negative correlation is seen between biomass of litter and flow resistivity. The higher the biomass of the litter, the lower the flow resistivity, this confirms the above suggested theorem. Dense litter packs could influence flow resistivity, although the $R^2$ is only 0.296. Variance in the response variable flow resistivity is also explained by other factors. Species tend to be quite uniform in values and form groups on the scatter plot. Lime stands out with profound differences between the two sample plots. Biomass does not differ that much ($\approx$11 g), so the flow resistivity makes the two sample plots dissimilar. The same is seen for a Maple2 measurement. No explanation can be given, unless local differences in soil properties or a very profound litter layer effect for these particular measurements.

Litter could have a beneficial impact in noise mitigation. This was already seen, but not fully quantified, by Reethof, Frank and McDaniel [58]. Pure acoustically, thick packs of litter would be optimal for transport noise. But when taking into account forest management ideas, it is a more nuanced answer. Litter quantity is mostly dependant on the turnover rate [76]. Low turnover rates are often associated with acidification of soils. Together with known acidification of road transport within close proximity of a road [102] and the effect of soils on forest ecosystems [103], this would mean a double effect of acidification. Thus optimal would be that forest are not roadside but further away from roads to lower acidifying impact. Then a lower portion of sound rays will interact with the ground and the ground effect will not be maximal. Something in between should be optimal.

Figure 4.8 shows an almost significant positive correlation. A dense area of measurements is seen because the bulk density did no differ a lot between species. Denser soil might be related to higher flow resistivities but more measurements are needed to confirm the results. This was expected because hard soils, very dense, have an infinitely high $\sigma$. Also grasslands with known higher flow resistivities [23] are characterised by higher bulk densities [104]. A measurement that is, again, noteworthy is Lime1. Again this measurement lies away from the other lime data points. But in this figure the differences for the independant variable are more or less explained. The higher value of the $\sigma_e$ corresponds with a higher bulk density. As mentioned before, stands of lime lie in the Adp soil class which is characterised by the absence of a layered soil profile. This could explain the heterogeneity, although not expected while Talaske found that only the first 10 cm of the soil matter for the examined frequency range [51]. The difference between white ash sample plots for bulk density cannot be explained.

Now these two previous effects were combined into one model, see Equation 4.1. In this regression, the effects bulk density and biomass are combined to predict the value of the flow resistivity. This model is significant but is still not enough to have strong evidence to predict the flow resisitivity. These two predictors together do not seem to be sufficient for a valuable flow resisitivity estimation.

### Layer depth and litter biomass

In the last figure of this series, Figure 4.9, a clear relation between the biomass and the litter layer depth is seen. This confirms the idea of packs of litter material having porous properties. This idea can be used to form an idea on how to use trees for sound mitigation. When litter biomass and layer depth are combined in a multiple regression model to predict the $\sigma_e$, it is strongly significant and $R^2$=0.614. This could be an interesting line of thought. Collecting litter and measuring the thickness of the litter layer would give an idea of the acoustical properties of a forest soil. This would cost a lot less time and material.

### Moisture effects on acoustical parameters

In contrary to what Cramond and Don found after conducting experiments on grass soils for moisture effects, higher moisture is higher $\sigma_e$ [57], no significant differences were found. Moreover the reverse was observed, although not significant. With increasing soil moisture content lower values of $\sigma_e$ were found. This is in line with what Reethof, Frank and McDaniel found, the beneficial effect on absorption of moist forest soils. Water does have higher flow resisitivity values than air thus was expected that when more water filled the pores a higher flow resisitivity would be found. This was not the case. Reethof, Frank and McDaniel concluded that this effect is because of changes in porosity [58]. Effects from soil moisture on porosity were not observed in the measurements. It has to be pointed out that experiments could not be conducted on the same site over a long period. Effects are now based on different species and plots which is not optimal.

For litter moisture no relationship were found. Litter moisture content did not influence $\sigma_e$ at all. With a very high p-value (0.961) it can be concluded that litter moisture content does not influence flow resisitivity. Moreover the effect of litter biomass seemed overrule the water content, when both effects were combined in a multiple regression model ($F(2,21)=5.1$, $p = 0.0157$). The effect of litter moisture content is not significant ($p = .33$) and the effect of litter biomass strongly significant ($p = 0.004$). The same goes for porosity, no effects from litter moisture on porosity. The moisture content of litter can thus be considered of minor importance.

# 6 | Conclusions

## 6.1 Modeling and set-up

It is clear that dimensioning a set-up for soil impedance measurements is more complicated than anticipated. Although a physically based model and method was used, efforts in fitting measurement data ended up in poor results. Two reasons led to the use of the standardized Nordtest method. The practical limitation of using a perfect point source outdoors, combined with the main focus on a measurement campaign. This method, also used by Attenborough [66], gave realistic sound pressure level difference spectra that could be fitted with models of increasing complexity. Step-by-step the model was increased from one to three parameters. The final step in modelling ended with a model that on average performed quite well with a low NT error in comparison to literature. This model also performed the best in the paper of Attenborough, Bashir and Taherzadeh in which ground impedance models are compared. The adequate results indicated that the Nordtest method was the right choice for ground impedance measurements.

## 6.2 Possible designs for woody vegetation belts

For the design of woody vegetation belts for noise mitigation the answer is nuanced and multi-layered. In most results it was clear that species tended to have an impact on the acoustic properties of the soil. The parameters derived from the data gathering were almost all significant between species and litter quality classes. Furthermore litter layer presence also seemed to have a significant impact. This means that advise could be given for planting certain species above other species. But, the species that came out of the research as the better noise mitigating species are also the species with dense litter packs. These species are associated with soil acidification [76]. In combination with the already present acidification by traffic emissions [102, 103], it seems that dense litter packs are not the best idea from a classic forest management perspective. An idea on mitigating soil acidification could be a mixture of species. For example northern red oak or beech in combination with species with more $Ca^{2+}$ in the litter. Nevertheless, the soil acidification effect might not be the main concern in a noise reduction belt. In that case it can be ignored and thick litter layer creating species are optimal.

Furthermore the stem effect cannot be ignored, a higher ground effect in combination with large stem abundance is also something that should aimed for. Scattering effects by stems, leaves and branches of higher frequencies combined with the low frequency affecting ground effect is the best. This could be done by maximizing multi-layer forest structure [105]. In fact a species like beech does well in dense forest and can survive in lower light conditions under the dominant canopy.

A summarizing depiction of the experiment is seen in Figure 6.1. Important to consider is that Cherry and AmAsh seem to be the best species here, with the deepest trough. When looking at beech and northern red oak, their graph is much wider, indicating an effect over more frequencies in the lower region ($<$1000 Hz). But, this is purely the ground effect, higher scattering by high density stands would change this figure drastically. An extra idea would be to combine species to broaden the frequency range that the ground would interfere with. To conclude, the frequency spectrum of the destructive interference for all species lies in that of transportation noise, see Figure 2.1.

## 6.3 Future research and ideas

It is assumed that loosening properties of soil by vegetation as suggested by Dobson and Ryan [54] could also be linked to earthworms *Lumbricidae* [98]. By linking acoustic porosity and earthworms, these could also affect the soil impedance. When earthworm activity or density is quantified together with acoustic properties of soils the effect of earthworms can be extracted. Higher porosity levels are important for more absorbing capacity, this could improve the ground effects of the species with faster litter turnover.

It could be interesting to install a roadside propagation experiment with species with thicker litter layers and species like sweet cherry and white ash. In this way the effects of combining different ground effect frequency minimums, see Figure 6.1, can be quantified.

The way the rigid backing is implemented can be questioned. In D&B and Z&K with rigid backing, Equation 3.2, the assumption is that the rigid backing is acoustically *hard*, this means that it completely reflects the incoming sound waves. In further research, the mineral soil parameters could be fitted on the measurement of the soil without the litter layer. Afterwards the second round of fitting would use the mineral layer parameters to characterise the rigid backing and thus create a two layer model generated from the measured data.

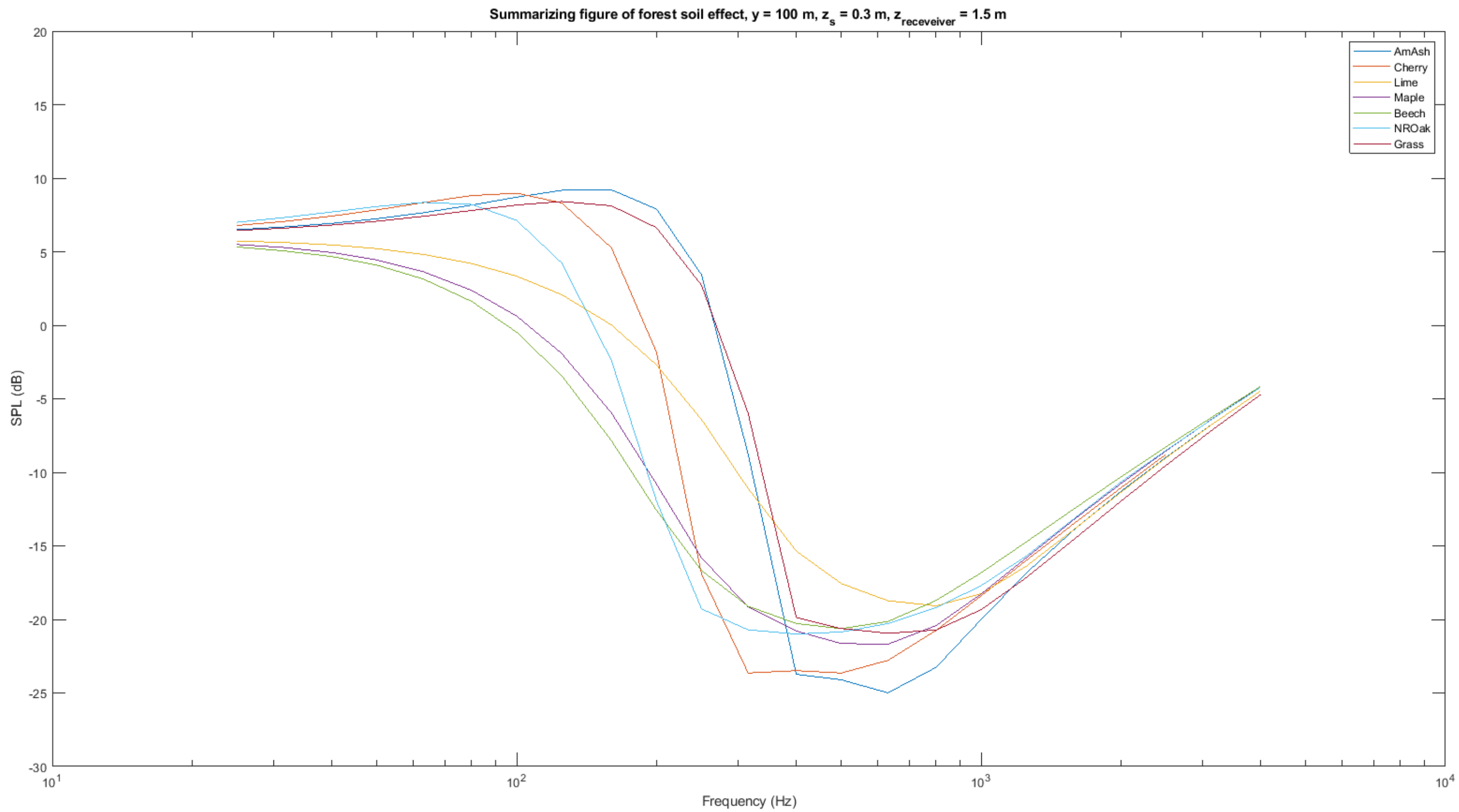



**Figure 6.1:** In this figure only the pure ground effect is seen, with on the y-axis the sound pressure level difference between the reflected path and free-field propagation and on the x-axis the different 1/3-octave bands. Distance from source to receivers is 100 m, height of source is 0.3 m and heigth of receiver is 1.5 m. As an extra reference a grass field is plotted as well, parameters from Attenborough, Bashir and Taherzadeh [66].

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# A | Set-up

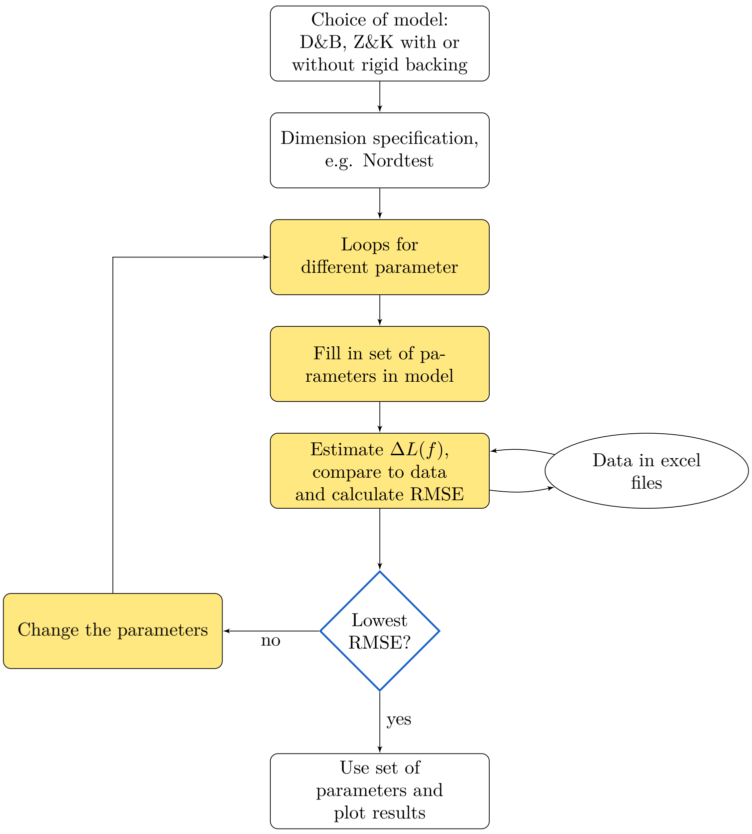



**Figure A.1:** Flowchart on how the brute force algorithm is performed by the MATLAB code. Yellow blocks indicate actions by the code and blue diamonds a decision.

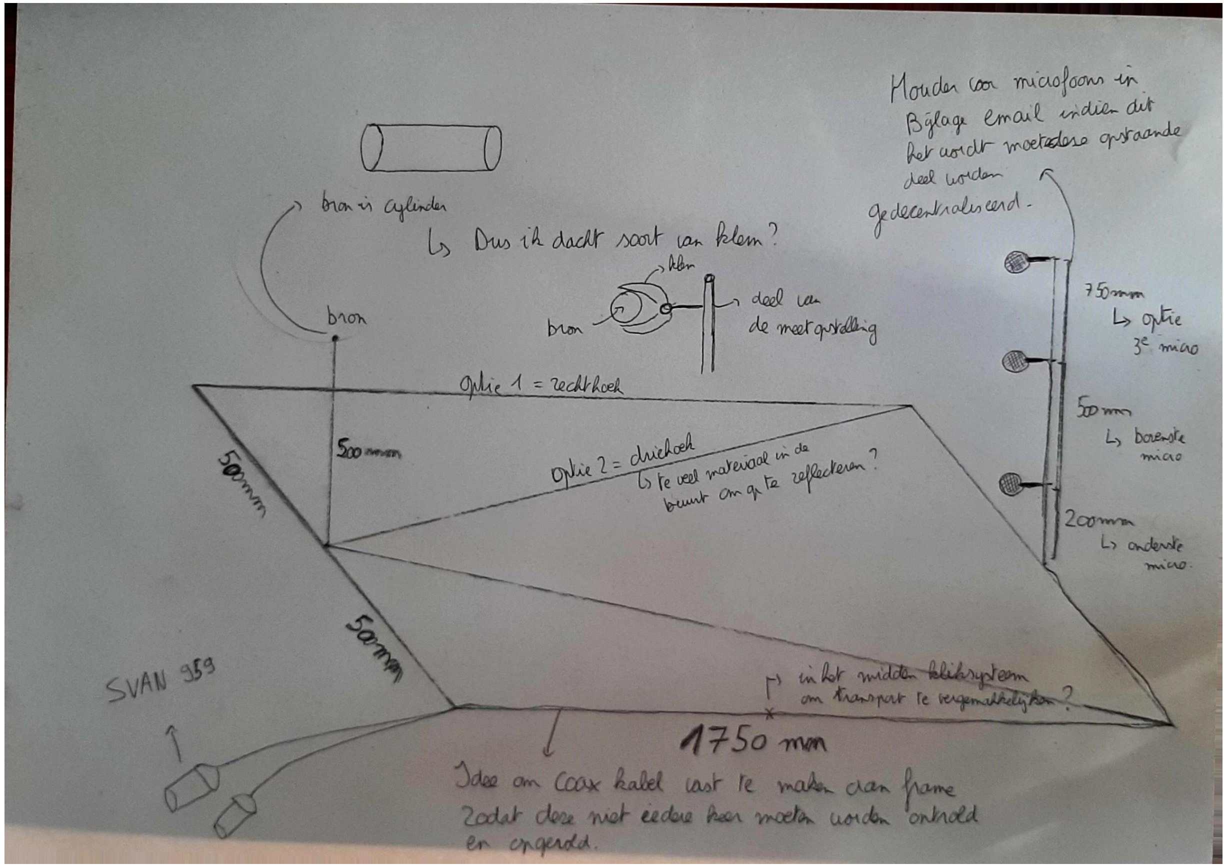



**Figure A.2:** Drawing of the plan after which the set-up is made. This was sent to the workshop where the set-up was constructed.

**Table A.1:** Raw data example of the output of the SVAN with only a limited amount of measurements. The rest is left out but this was only to provide an output example of the data logger.

| No. | Date & time | $L_A$ peak | $L_A$ min | $L_A$ max | 20 Hz | 25 Hz | 31.5 Hz | 40 Hz | 50 Hz | 63 Hz | 80 Hz | 100 Hz | 125 Hz | 160 Hz | 200 Hz | 250 Hz | 315 Hz | 400 Hz | 500 Hz | 630 Hz |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 09/11/2019 14:59:42.200 | 53,8 | 42,6 | 40,3 | 1,9 | -5,1 | 3,9 | 11,2 | 9,6 | 25,8 | 21 | 22,5 | 17,1 | 28,8 | 31,5 | 30,4 | 32,5 | 32,1 | 33,2 | 32,4 |
| 2 | 09/11/2019 14:59:42.400 | 53,6 | 43,5 | 42,5 | 1,4 | -2,1 | -5,1 | 6,2 | 12,1 | 24,8 | 16,9 | 27,2 | 19,2 | 27,3 | 32,9 | 29,5 | 33,3 | 31,9 | 34 | 33,2 |
| 3 | 09/11/2019 14:59:42.600 | 56,3 | 43,9 | 43,2 | 6,9 | 0,9 | 9,4 | 11,8 | 12 | 25,4 | 19,5 | 27,6 | 19,1 | 25,8 | 33,6 | 29,5 | 32,4 | 31,2 | 34 | 33,4 |
| 4 | 09/11/2019 14:59:42.800 | 54,3 | 43,7 | 43,1 | 7,5 | -3,3 | 6,8 | 11,8 | 13,5 | 25,3 | 21 | 27,5 | 19,6 | 26,1 | 31,5 | 29,7 | 33,4 | 31,2 | 31,1 | 32,8 |
| 5 | 09/11/2019 14:59:43.000 | 54 | 43,7 | 43 | 7,5 | 3 | 4,7 | 6,9 | 11,7 | 24,3 | 17,5 | 25,8 | 19,3 | 30,2 | 29,4 | 29,9 | 30,9 | 29,9 | 33,8 | 31,6 |
| 6 | 09/11/2019 14:59:43.200 | 54,9 | 43,5 | 43,2 | 7,5 | 1,9 | 9,2 | 4,2 | 10,3 | 24,8 | 22,5 | 27,3 | 19,1 | 28,6 | 32,1 | 30,6 | 31,1 | 31,5 | 31,7 | 31,5 |
| 7 | 09/11/2019 14:59:43.400 | 54,6 | 43,7 | 43,2 | 7,5 | 0,9 | 7,7 | 8,5 | 10,7 | 25 | 21,7 | 27,1 | 19,5 | 28,3 | 32,2 | 31,2 | 31 | 30,1 | 33,1 | 33,1 |
| 8 | 09/11/2019 14:59:43.600 | 54,2 | 43,6 | 43 | 7,5 | 5,5 | 4,4 | 11,5 | 11,8 | 26 | 21,9 | 27,3 | 19,4 | 26 | 28,7 | 31,4 | 31,8 | 29,6 | 32,7 | 31,4 |
| 9 | 09/11/2019 14:59:43.800 | 54,2 | 44 | 43,6 | 7,5 | 0,3 | 4,2 | 9,8 | 11,8 | 25,5 | 23,8 | 25,6 | 19,8 | 28,1 | 30,5 | 30,1 | 31,6 | 31,5 | 32,4 | 32,3 |
| 10 | 09/11/2019 14:59:44.000 | 53,2 | 43,6 | 42,4 | 7,5 | 5,1 | 6,9 | 11 | 7,2 | 24,9 | 23,1 | 22 | 17,7 | 26,3 | 27,4 | 30,3 | 32,2 | 32,1 | 31,5 | 31,8 |
| 11 | 09/11/2019 14:59:44.200 | 53,7 | 42,6 | 42,2 | 7,5 | 1,4 | 6,7 | 11,8 | 8,4 | 25 | 24,8 | 17 | 20,2 | 22,6 | 28,4 | 30,6 | 30,8 | 33 | 31,7 | 31,9 |
| 12 | 09/11/2019 14:59:44.400 | 53,8 | 42,7 | 42,3 | 7,5 | -0,3 | 10,6 | 13,4 | 12,3 | 25,5 | 20,2 | 24,6 | 19,3 | 27,1 | 27,4 | 31,2 | 30,6 | 30,7 | 32,3 | 32,3 |
| 13 | 09/11/2019 14:59:44.600 | 53,2 | 42,9 | 42,4 | 7,5 | -2,1 | 0,9 | 8,1 | 14,1 | 24,8 | 22,9 | 27,3 | 22,4 | 24,5 | 28,6 | 30,8 | 31,5 | 31,6 | 33,6 | 31,7 |
| 14 | 09/11/2019 14:59:44.800 | 54,8 | 43 | 42,6 | 7,5 | 8,7 | 9,7 | 12,8 | 14,6 | 25,2 | 22 | 28,7 | 16,9 | 23,1 | 28,4 | 29,1 | 31,3 | 31,4 | 33 | 32,7 |
| 15 | 09/11/2019 14:59:45.000 | 53,4 | 43,3 | 42,9 | 6 | 2,7 | 8,6 | 11,9 | 14,6 | 22,8 | 24,3 | 28,8 | 18,7 | 25,3 | 28,8 | 31,1 | 30,9 | 31,9 | 32,9 | 33 |
| 16 | 09/11/2019 14:59:45.200 | 54,3 | 43,2 | 42,7 | 6,8 | -5,1 | 5,9 | 9,7 | 7,8 | 24,2 | 21,6 | 27,5 | 19,7 | 26,4 | 28,7 | 30,6 | 30,7 | 31,7 | 32,3 | 31,6 |
| 17 | 09/11/2019 14:59:45.400 | 55,1 | 43,3 | 42,7 | 6,7 | 0,3 | -1,1 | 6,8 | 8,5 | 24,4 | 23,7 | 25,1 | 17,7 | 26,2 | 29,1 | 32,7 | 31,1 | 32 | 32,9 | 33,6 |
| 18 | 09/11/2019 14:59:45.600 | 53,9 | 43,2 | 42,6 | 3,9 | -0,3 | 4,9 | 6,5 | 5,9 | 22,5 | 21,5 | 23,4 | 19,5 | 24,1 | 32,3 | 30 | 32,3 | 32,4 | 31,8 | 32,8 |
| 19 | 09/11/2019 14:59:45.800 | 53,1 | 42,9 | 42,6 | 1,9 | -5,7 | 6,7 | 11,2 | 11,4 | 23,7 | 19,1 | 18,1 | 21,3 | 22,6 | 31,7 | 33,1 | 31,3 | 31,2 | 33,2 | 33,2 |
| 20 | 09/11/2019 14:59:46.000 | 54,9 | 43,1 | 42,5 | 1,9 | -5,7 | 3,7 | 13,9 | 13,8 | 21,8 | 25,4 | 23 | 19,8 | 24,6 | 33,5 | 31,8 | 32,8 | 32 | 31,7 | 31,8 |
| 21 | 09/11/2019 14:59:46.200 | 54,1 | 43,1 | 42,6 | 1,4 | -0,3 | 3 | 9,3 | 8,4 | 23,4 | 22,1 | 27,9 | 17,6 | 28 | 32,5 | 31,1 | 29,7 | 31,5 | 31,7 | 32,5 |
| 22 | 09/11/2019 14:59:46.400 | 54,8 | 43,6 | 42,9 | 2,7 | 3,7 | -2,1 | 7,8 | 8,3 | 21,3 | 23,6 | 29,2 | 15,7 | 24,1 | 32,3 | 32,1 | 33,7 | 31,7 | 32,7 | 33,9 |
| 23 | 09/11/2019 14:59:46.600 | 54,8 | 44 | 43,5 | 3,4 | -3,3 | 10,2 | 5,9 | 10,6 | 22,7 | 16,2 | 26,2 | 19,8 | 23,8 | 31,5 | 32,2 | 35,8 | 32,5 | 34,7 | 34 |
| 24 | 09/11/2019 14:59:46.800 | 55,9 | 44,7 | 43,8 | 2,7 | -5,1 | 3 | 8 | 14,2 | 21,4 | 24,8 | 25,6 | 19,8 | 24,2 | 29 | 30,9 | 35 | 34,3 | 35,8 | 34,4 |
| 25 | 09/11/2019 14:59:47.000 | 55,5 | 45,2 | 44,4 | 1,9 | -5,1 | 10 | 11,5 | 13,5 | 21,8 | 21,4 | 21,1 | 19,2 | 25,3 | 32,3 | 31,9 | 36,4 | 35,7 | 37,9 | 35,5 |
| 26 | 09/11/2019 14:59:47.200 | 55,1 | 45,3 | 44,5 | 1,4 | 3,7 | 6 | 12,5 | 8,1 | 22,7 | 19,2 | 27,2 | 19 | 23,6 | 30,6 | 31,6 | 36,6 | 33,9 | 37,2 | 34,9 |
| 27 | 09/11/2019 14:59:47.400 | 56,5 | 45 | 44,3 | 1,9 | -0,3 | 3 | 7,6 | 13,6 | 23,4 | 22,3 | 30,8 | 24 | 25 | 27,8 | 32,5 | 36,2 | 34,6 | 36,4 | 35 |
| 28 | 09/11/2019 14:59:47.600 | 55,5 | 45,1 | 43,9 | 2,7 | 0,3 | 2,3 | 9,1 | 9,3 | 23,8 | 23,2 | 28,1 | 23,1 | 26,2 | 28,7 | 32,9 | 36 | 33,5 | 36,6 | 33,4 |
| 29 | 09/11/2019 14:59:47.800 | 54,6 | 44,1 | 43,7 | 3,4 | -0,3 | 8,5 | 11,8 | 6,2 | 22,3 | 22,7 | 27,7 | 22,6 | 25,4 | 28,3 | 28,8 | 33,9 | 33,7 | 34,7 | 34 |
| 30 | 09/11/2019 14:59:48.000 | 55,8 | 44,9 | 43,9 | 2,7 | 3 | 0,9 | 8,3 | 12,4 | 23,4 | 24,8 | 31,7 | 23,4 | 24,9 | 30 | 32,1 | 35,3 | 34,7 | 38,1 | 33,9 |
| 31 | 09/11/2019 14:59:48.200 | 57,5 | 44,9 | 44,4 | 1,4 | 5,5 | 7,6 | 10,6 | 11,6 | 23,2 | 23,4 | 27,1 | 23,1 | 26,5 | 31,2 | 30,7 | 35,1 | 34,7 | 35,2 | 33,7 |
| 32 | 09/11/2019 14:59:48.400 | 55 | 44,6 | 44,1 | 1,9 | -5,1 | 8,8 | 7,2 | 12,1 | 23,5 | 22,1 | 31,3 | 25,2 | 27,3 | 33 | 32,9 | 34 | 33,7 | 35,9 | 33,3 |
| 33 | 09/11/2019 14:59:48.600 | 54,8 | 44,7 | 44,3 | 1,9 | 0,3 | 5,1 | 7,7 | 14 | 22,4 | 21,6 | 25,3 | 26,2 | 28,6 | 34,9 | 32,5 | 35,4 | 32,6 | 35,5 | 34,6 |
| 34 | 09/11/2019 14:59:48.800 | 57,4 | 45,9 | 44,5 | 3 | 0,3 | 8,3 | 11,8 | 9,4 | 24,6 | 22,5 | 27,8 | 26,8 | 30,6 | 36,3 | 33,2 | 35,8 | 33,8 | 37,2 | 36,6 |
| 35 | 09/11/2019 14:59:49.000 | 57 | 46 | 45,5 | 3 | 6 | 5,3 | 11,1 | 9,9 | 24,7 | 26,3 | 29,3 | 26,7 | 27,3 | 33,6 | 34,1 | 33,2 | 34 | 36,9 | 37,6 |
| 36 | 09/11/2019 14:59:49.200 | 55,8 | 45,5 | 44,6 | 2,7 | 0,9 | 9,2 | 3,7 | 7,3 | 24,3 | 25,2 | 26,5 | 24,4 | 27,8 | 32,1 | 33,1 | 34,2 | 32,4 | 35,3 | 35,3 |
| 37 | 09/11/2019 14:59:49.400 | 56 | 45 | 44,5 | 1,4 | -2,1 | 7,1 | 6,7 | 13,7 | 25,2 | 24,2 | 27,7 | 28,2 | 29,1 | 32,8 | 33,1 | 35,6 | 34,2 | 34,4 | 34,7 |
| 38 | 09/11/2019 14:59:49.600 | 56,3 | 45,4 | 44,6 | 1,9 | 0,9 | 8,6 | 11,2 | 11,4 | 25,3 | 26,4 | 27,6 | 28,8 | 29,9 | 32,5 | 32 | 35,5 | 36,7 | 35,4 | 35,4 |
| 39 | 09/11/2019 14:59:49.800 | 56,9 | 46,1 | 45,1 | 2,3 | 0,3 | 1,4 | 9,6 | 10,9 | 23,9 | 27,3 | 25,5 | 26,6 | 31,2 | 31,1 | 34,7 | 37,9 | 36,1 | 36,5 | 36,1 |
| 40 | 09/11/2019 14:59:50.000 | 57,5 | 46,2 | 45,7 | 3 | 3,9 | 10,9 | 9,4 | 11 | 24,1 | 27,4 | 23,9 | 25,3 | 31 | 32,1 | 37 | 35,5 | 34,7 | 37,1 | 36,2 |

| No. | 800 Hz | 1000 Hz | 1250 Hz | 1600 Hz | 2000 Hz | 2500 Hz | 3150 Hz | 4000 Hz | 5000 Hz | 6300 Hz | 8000 Hz | 10000 Hz | 12500 Hz | 16000 Hz | 20000 Hz | Total A | Total C | Total Z |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 32,8 | 34,1 | 31,6 | 29,6 | 28,2 | 28 | 27,8 | 27,5 | 25,6 | 23,2 | 19 | 14,3 | 8,8 | 5,3 | 5,7 | 43,1 | 54,3 | 72,1 |
| 2 | 33,9 | 33,5 | 30,3 | 28,4 | 28,9 | 28,1 | 27,8 | 27,9 | 25,5 | 23,4 | 19,2 | 14,5 | 9,1 | 4,4 | 5,5 | 43,5 | 55,2 | 65,8 |
| 3 | 33,3 | 35,7 | 31,9 | 29,6 | 28,1 | 28,2 | 27,6 | 27,9 | 25,7 | 23,4 | 19,4 | 14,7 | 9,2 | 4,7 | 5,3 | 43,5 | 55,5 | 74,2 |
| 4 | 34,7 | 35,4 | 31,8 | 29,7 | 28,1 | 28,3 | 28,7 | 27,6 | 26 | 23,8 | 19,3 | 14,7 | 8,7 | 4,7 | 5,1 | 43,6 | 54,9 | 69,7 |
| 5 | 34,7 | 35,5 | 31,9 | 29,6 | 28,2 | 27,7 | 28,5 | 27,7 | 26,6 | 23,1 | 19,6 | 14,6 | 9 | 4,7 | 5,7 | 43,2 | 54,7 | 65 |
| 6 | 35,3 | 35,1 | 32,4 | 30,4 | 28,3 | 28,5 | 28,4 | 27,7 | 25,9 | 23,3 | 19,5 | 14,8 | 9,1 | 4,7 | 5,3 | 43,4 | 55,1 | 60,8 |
| 7 | 34 | 36,2 | 32,9 | 29 | 28,7 | 28,8 | 27,4 | 26,9 | 26,2 | 23 | 18,9 | 14,4 | 8,9 | 5,3 | 5,7 | 43,6 | 55,1 | 65,3 |
| 8 | 33,3 | 36,9 | 32,5 | 28,8 | 28,2 | 28,1 | 28,3 | 27,5 | 25,7 | 23,4 | 18,7 | 14,1 | 9,1 | 4,7 | 5,7 | 43,4 | 54,9 | 64 |
| 9 | 34,2 | 38,8 | 32,3 | 28 | 28 | 27,5 | 28,2 | 26,9 | 25,3 | 22,8 | 18,5 | 14 | 8,8 | 4,9 | 5,7 | 43,8 | 55,2 | 57,8 |
| 10 | 31,4 | 33,6 | 30,4 | 29,3 | 27,6 | 27,5 | 27,6 | 27,3 | 24,9 | 22,5 | 18,4 | 13,6 | 8,7 | 4,7 | 5,5 | 42,1 | 54,3 | 63,8 |
| 11 | 32 | 33 | 30,9 | 29,1 | 28,7 | 27,1 | 27,4 | 26,6 | 24,8 | 22,1 | 18,1 | 13,5 | 8,1 | 4,4 | 5,5 | 42,3 | 54,9 | 67,8 |
| 12 | 33,3 | 35,5 | 31,7 | 28,5 | 27,3 | 27,3 | 26,9 | 26,1 | 24,8 | 22,1 | 18 | 13,5 | 8,9 | 4,7 | 5,3 | 42,7 | 54,9 | 65,9 |
| 13 | 31,7 | 34,8 | 30,9 | 27,8 | 27,8 | 27,3 | 27,3 | 26,1 | 23,9 | 21,2 | 17,7 | 13,3 | 9,1 | 5,5 | 6 | 42,7 | 55,3 | 65,6 |
| 14 | 32,7 | 36,5 | 31,4 | 29 | 27,2 | 26,5 | 27,5 | 26,2 | 25 | 22,6 | 19,1 | 15,9 | 12,6 | 10 | 8 | 42,9 | 54,6 | 60,8 |
| 15 | 32,9 | 37 | 30,6 | 28,8 | 27,3 | 28,1 | 27,2 | 26,5 | 25,5 | 23,7 | 20,5 | 18,6 | 15,2 | 12,6 | 11 | 43,3 | 55 | 65 |
| 16 | 32 | 36,1 | 31,7 | 27,9 | 27 | 26,8 | 26,5 | 26,2 | 24,5 | 23,1 | 20,3 | 16,4 | 13,9 | 11,9 | 10,1 | 42,8 | 54,4 | 63,7 |
| 17 | 32,9 | 35,3 | 31 | 28,8 | 27,3 | 27,4 | 26,5 | 26,8 | 24,7 | 22,6 | 19,4 | 17,3 | 14,9 | 12,5 | 9,7 | 43 | 53,5 | 65,3 |
| 18 | 31,7 | 35,3 | 31,2 | 29,7 | 27,5 | 27,1 | 26,8 | 26,3 | 24,4 | 21,8 | 18,1 | 15,2 | 11,7 | 9 | 7,2 | 42,7 | 53,3 | 61,6 |
| 19 | 32,7 | 33,5 | 30,5 | 28,9 | 27,7 | 27 | 26,8 | 26,1 | 24,1 | 21,8 | 18,2 | 14,7 | 11,8 | 9,1 | 7,7 | 42,6 | 53,6 | 65,9 |
| 20 | 32,4 | 33,4 | 31,3 | 29,4 | 27,5 | 26,7 | 26,9 | 25,7 | 24,3 | 22,1 | 18,7 | 14,9 | 12,3 | 9,9 | 8,1 | 42,9 | 54,4 | 65,1 |
| 21 | 33,2 | 34,2 | 30,7 | 29,3 | 28,4 | 27,4 | 27 | 26,5 | 24,5 | 23,1 | 19,5 | 17,1 | 15 | 13,5 | 11,2 | 42,9 | 54,4 | 58,4 |
| 22 | 33,4 | 35,8 | 31,3 | 29,4 | 27,2 | 27 | 27,2 | 26,6 | 24,7 | 23,3 | 20,5 | 18,5 | 15,6 | 13,4 | 10,1 | 43,7 | 54,5 | 59,1 |
| 23 | 35,8 | 34,6 | 31,2 | 29,5 | 27,9 | 26,6 | 27,1 | 25,8 | 24,4 | 21,6 | 17,6 | 14,2 | 9,9 | 7,5 | 6,5 | 43,9 | 53,5 | 57,9 |
| 24 | 35,8 | 37,8 | 32 | 29,5 | 27,4 | 26,5 | 26 | 25,5 | 23,5 | 21,2 | 17,2 | 13,6 | 9,7 | 8,3 | 6,2 | 44,7 | 54,9 | 61,8 |
| 25 | 35 | 36 | 32,4 | 28,4 | 27,5 | 26,7 | 26,6 | 25,4 | 23,2 | 20,6 | 16,8 | 12,7 | 8,4 | 4,7 | 5,7 | 45,2 | 54,2 | 67,5 |
| 26 | 35,1 | 35,6 | 32,6 | 29,4 | 27,6 | 26,7 | 26,1 | 25,3 | 23,7 | 20,9 | 16,8 | 12,7 | 8,3 | 4,7 | 5,5 | 44,6 | 54,5 | 60,2 |
| 27 | 35,5 | 35 | 32,2 | 29,5 | 27,4 | 26,4 | 25,9 | 25 | 23,9 | 21 | 17,9 | 14,5 | 10,3 | 7,7 | 6,5 | 44,8 | 55,2 | 70,2 |
| 28 | 34,2 | 33,4 | 32,5 | 29,7 | 27,5 | 27,5 | 25,7 | 24,7 | 23,8 | 21,8 | 18 | 14,9 | 11,8 | 8,4 | 7,2 | 44,1 | 54,4 | 65,7 |
| 29 | 35,6 | 34,1 | 32,4 | 29,8 | 28 | 27,2 | 26,9 | 25,9 | 24,3 | 21,8 | 17,9 | 15,2 | 12,2 | 9,3 | 7,5 | 43,8 | 54,9 | 65,5 |
| 30 | 34,9 | 36,6 | 32,6 | 29,5 | 27,1 | 27 | 26,8 | 25,3 | 23,7 | 21,1 | 18 | 14,4 | 10,9 | 8,5 | 7,2 | 45 | 55,9 | 60 |
| 31 | 34,8 | 37,7 | 33,1 | 29,1 | 27,7 | 26,2 | 25,8 | 25,4 | 23,8 | 20,8 | 17,8 | 14,5 | 11,2 | 9,1 | 7,5 | 44,4 | 54,5 | 70,2 |
| 32 | 33,1 | 36 | 31,4 | 28,9 | 27 | 25,4 | 26,2 | 26,2 | 24,5 | 22,4 | 20,1 | 15,2 | 12,3 | 9,1 | 7,8 | 44,4 | 55,6 | 66,8 |
| 33 | 33,6 | 35,4 | 32,8 | 30 | 27,4 | 26,7 | 26,6 | 25,8 | 24 | 22,9 | 20,4 | 20,1 | 17,2 | 13,7 | 10,1 | 44,5 | 54,8 | 72,3 |
| 34 | 36,1 | 37,4 | 33,9 | 31,4 | 27,1 | 26,5 | 26,6 | 25,2 | 23,4 | 22,2 | 21,3 | 19,4 | 18,4 | 15,3 | 11,8 | 46 | 56,5 | 66,6 |
| 35 | 35,9 | 37,5 | 32,9 | 31,7 | 27,4 | 25,8 | 25,8 | 24,8 | 23 | 20,5 | 17,8 | 15,2 | 12,6 | 10,3 | 8,1 | 45,5 | 56,5 | 67,4 |
| 36 | 35,9 | 35 | 32,6 | 31,2 | 27,1 | 26,1 | 25,9 | 24,5 | 23,1 | 19,9 | 16,7 | 13,2 | 9,1 | 6,2 | 5,9 | 44,5 | 55,5 | 63,8 |
| 37 | 36,6 | 35,7 | 32,6 | 30,4 | 26,9 | 25,9 | 25,1 | 25,1 | 22,5 | 20 | 16,4 | 12,9 | 8,6 | 5,1 | 5,3 | 44,7 | 55,8 | 67,2 |
| 38 | 35,9 | 36 | 32,3 | 29,1 | 26,6 | 25,7 | 24,7 | 24,7 | 22,8 | 20 | 16,1 | 12,7 | 7,7 | 4,2 | 5,3 | 45,2 | 56,3 | 72,2 |
| 39 | 36,9 | 37 | 34,4 | 30,8 | 26,9 | 25,2 | 25,4 | 24 | 22,3 | 20,1 | 16,5 | 12,1 | 7,7 | 4,4 | 5,3 | 46,2 | 57 | 69,2 |
| 40 | 37,9 | 37,4 | 33 | 29,5 | 27,3 | 25,7 | 25 | 24,2 | 22,8 | 20,4 | 16,5 | 12,4 | 8,2 | 4,7 | 5,5 | 45,9 | 55,5 | 72,7 |

# B | Forest

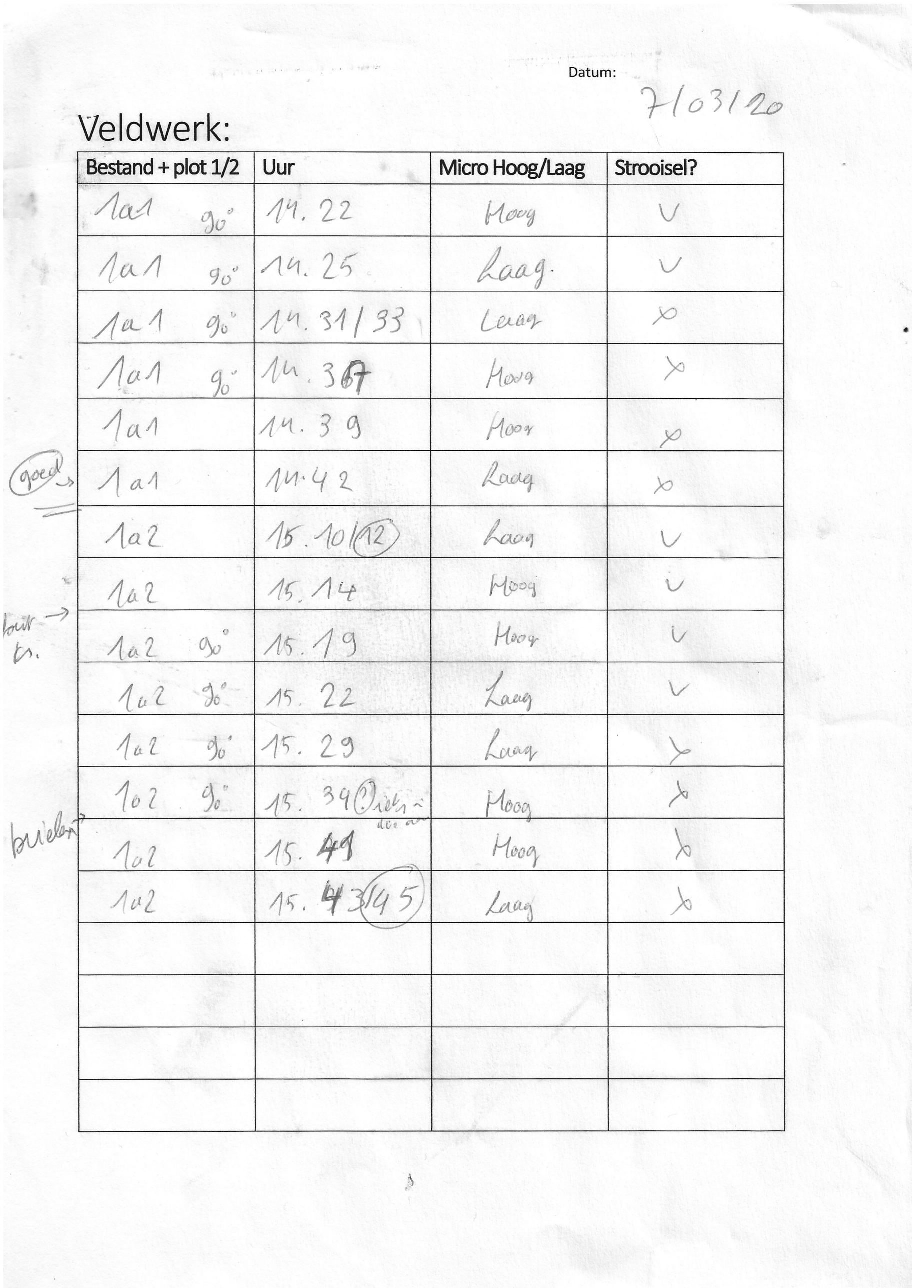
In this chapter a bit more extra info on the fieldwork will be provided. Besides that also raw data of the non-acoustical soil characteristics and some raw plots will be presented to complete the dissertation.

The fieldwork was organised on three dates when the weather was good enough to measure. Good is defined as no precipitation during measurements and little wind. This was the case on February 24th, March 6th and 7th, see Table B.1. Measurement data is from the weather station in Beitem. This is the closest one to the Mortagne-forest. Height of the measurement of wind speed is estimated at 10m. Precipitation is amount of mm accumulated that day before measurements.
On these three dates the six plots where visited and the protocol, described in section 3.5, was done. The idea was to do the acoustic measurements and the non-acoustical soil characteristic sampling simultaneously to obtain the actual conditions. Everything was coded and timestamps of measurements were written down on the exact moment to be able to link SVANTEK-files afterwards Figure B.1.

**Table B.1:** The most important weather parameters during the days of the field campaign [106]

| Date | Average wind speed[1] (m $s^{-1}$) | Precipitation (mm) |
|---|---|---|
| 24 February 2020 | 5 | 0.8 |
| 6 March 2020 | 6.6 | 10[2] |
| 7 March 2020 | 4.2 | 0.3 |

[2]The precipitation fell in the morning, measurements only started when it was not raining.



Datum: 7/03/20

Veldwerk:

| Bestand + plot 1/2 | Uur | Micro Hoog/Laag | Strooisel? |
|---|---|---|---|
| 1a1 90° | 14.22 | Hoog | V |
| 1a1 90° | 14.25 | Laag | V |
| 1a1 90° | 14.31/33 | Laag | X |
| 1a1 90° | 14.37 | Hoog | X |
| 1a1 | 14.39 | Hoog | X |
| 1a1 | 14.42 | Laag | X |
| 1a2 | 15.10/12 | Laag | V |
| 1a2 | 15.14 | Hoog | V |
| 1a2 90° | 15.19 | Hoog | V |
| 1a2 90° | 15.22 | Laag | V |
| 1a2 90° | 15.29 | Laag | X |
| 1a2 90° | 15.34 | Hoog | X |
| 1a2 | 15.41 | Hoog | X |
| 1a2 | 15.43/45 | Laag | X |
| | | | |
| | | | |
| | | | |
| | | | |

**Figure B.1:** Example of the sheet that is filled in during the fieldwork. This is an example of the white ash plots. The time of the measurement is very important to later link the SVANTEK file with the measurement set-up settings. In this way it was hard to make mistakes during the data processing.

**Table B.2:** Table containing the raw collected data of the soil samples and first calculations. See Equation 3.10 and 3.11 on how these were calculated. (ID's with a * at the end, indicate measurements that where not utilized for calculations.)

| ID | Weight moist (g) | Weight dry (g) | Gravimetric water content (g $g^{-1}$) | Bulk density (g $cm^{-3}$) |
|---|---|---|---|---|
| 1a1a | 113.37 | 79.25 | 1.13 | 0.43 |
| 1a1b | 174.43 | 129.38 | 1.74 | 0.35 |
| 1a1c | 152.78 | 113.09 | 1.53 | 0.35 |
| 1a1d | 149.87 | 113.4 | 1.50 | 0.32 |
| 1a2a | 156.80 | 117.7 | 1.57 | 0.33 |
| 1a2b | 128.08 | 76.44 | 1.28 | 0.68 |
| 1a2c | 105.60 | 61.56 | 1.06 | 0.72 |
| 1a2d | 170.71 | 120.18 | 1.71 | 0.42 |
| 5c1a | 154.60 | 115.53 | 1.55 | 0.34 |
| 5c1b | 145.62 | 102.13 | 1.46 | 0.43 |
| 5c1c | 112.69 | 80.23 | 1.13 | 0.40 |
| 5c1d | 159.16 | 118.5 | 1.59 | 0.34 |
| 5c2a | 164.56 | 116.92 | 1.65 | 0.41 |
| 5c2b | 125.75 | 85.63 | 1.26 | 0.47 |
| 5c2c | 170.92 | 120.95 | 1.71 | 0.41 |
| 5c2d | 109.29 | 74.62 | 1.09 | 0.46 |
| 5a1a | 159.98 | 125.94 | 1.60 | 0.27 |
| 5a1b | 152.21 | 111.88 | 1.52 | 0.36 |
| 5a1c | 163.25 | 115.23 | 1.63 | 0.42 |
| 5a1d* | | | | |
| 5a2a | 129.42 | 96.26 | 1.29 | 0.34 |
| 5a2b | 149.41 | 100 | 1.49 | 0.49 |
| 5a2c | 139.61 | 93.23 | 1.40 | 0.50 |
| 5a2d | 139.29 | 105.66 | 1.39 | 0.32 |
| 8a1a | 142.05 | 118.72 | 1.42 | 0.20 |
| 8a1b | 154.69 | 105.08 | 1.55 | 0.47 |
| 8a1c | 130.81 | 92.82 | 1.31 | 0.41 |
| 8a1d | 112.65 | 73.5 | 1.13 | 0.53 |
| 8a2a | 136.86 | 99.58 | 1.37 | 0.37 |
| 8a2b | 133.92 | 93.52 | 1.34 | 0.43 |
| 8a2c | 113.06 | 81.57 | 1.13 | 0.39 |
| 8a2d | 130.18 | 88.6 | 1.30 | 0.47 |
| 6c1a | 132.32 | 67.27 | 1.32 | |
| 6c1b | 165.70 | 126 | 1.66 | 0.32 |
| 6c1c | 129.88 | 70.31 | 1.30 | 0.85 |
| 6c1d | 152.97 | 99.75 | 1.53 | 0.53 |
| 6c2a | 156.47 | 117.59 | 1.56 | 0.33 |
| 6c2b | 153.93 | 109.73 | 1.54 | 0.40 |
| 6c2c | 111.70 | 74.08 | 1.12 | 0.51 |
| 6c2d | 142.96 | 90.5 | 1.43 | 0.58 |
| 6a1a* | 155.01 | 117.63 | 1.55 | 0.32 |
| 6a1b | 153.22 | 118.39 | 1.53 | 0.29 |

**Table B.2 continued from previous page**

| ID | Weight moist (g) | Weight dry (g) | Gravimetric water content (g $g^{-1}$) | Bulk density (g $cm^{-3}$) |
|---|---|---|---|---|
| 6a1c | 123.81 | 87.72 | 1.24 | 0.41 |
| 6a1d | 127.59 | 85.41 | 1.28 | 0.49 |
| 6a2a | 130.34 | 102.77 | 1.30 | 0.27 |
| 6a2b | 145.29 | 108.48 | 1.45 | 0.34 |
| 6a2c | 111.86 | 67.89 | 1.12 | 0.65 |
| 6a2d | 106.68 | 67.99 | 1.07 | 0.57 |

**Table B.3:** Table with the raw data of the litter layer samples. The litter is shown dry and moist and for the calculation of the gravimetric water content autorefovendry.

| ID | Weight moist (g) | Weight dry (g) | Gravimetric water content (g $g^{-1}$) |
|---|---|---|---|
| 1a1a | 90.67 | 21.90 | 3.14 |
| 1a1b | 79.66 | 19.24 | 3.14 |
| 1a1c | 122.67 | 38.15 | 2.22 |
| 1a2a | 79.32 | 21.88 | 2.63 |
| 1a2b | 87.73 | 22.04 | 2.98 |
| 1a2c | 81.66 | 18.46 | 3.42 |
| 5c1a | 27.9 | 14.46 | 0.93 |
| 5c1b | 77.92 | 26.94 | 1.89 |
| 5c1c | 90.75 | 33.91 | 1.68 |
| 5c2a | 209.03 | 57.39 | 2.64 |
| 5c2b | 62.92 | 21.28 | 1.96 |
| 5c2c | 161.55 | 49.56 | 2.26 |
| 5a1a | 69.92 | 24.26 | 1.88 |
| 5a1b | 35.98 | 7.45 | 3.83 |
| 5a1c | 105.92 | 34.47 | 2.07 |
| 5a2a | 93.24 | 22.34 | 3.17 |
| 5a2b | 168.97 | 37.45 | 3.51 |
| 5a2c | 214.23 | 41.40 | 4.17 |
| 8a1a | 94.36 | 18.31 | 4.15 |
| 8a1b | 92.82 | 24.16 | 2.84 |
| 8a1c | 69.88 | 16.01 | 3.36 |
| 8a2a | 125.6 | 19.09 | 5.58 |
| 8a2b | 90.7 | 26.59 | 2.41 |
| 8a2c | 70.15 | 21.83 | 2.21 |
| 6c1a | 146.5 | 44.89 | 2.26 |
| 6c1b | 107.03 | 32.60 | 2.28 |
| 6c1c | 258.27 | 67.76 | 2.81 |
| 6c2a | 194.02 | 52.43 | 2.70 |
| 6c2b | 277.62 | 69.45 | 3.00 |

**Table B.3 continued from previous page**

| ID | Weight moist (g) | Weight dry (g) | Gravimetric water content (g $g^{-1}$) |
|---|---|---|---|
| 6c2c | 264.88 | 69.77 | 2.80 |
| 6a1a | 182.02 | 60.97 | 1.99 |
| 6a1b | 134.27 | 37.73 | 2.56 |
| 6a1c | 143.83 | 35.68 | 3.03 |
| 6a2a | 190.89 | 62.89 | 2.04 |
| 6a2b | 239.26 | 82.31 | 1.91 |
| 6a2c | 120.53 | 46.65 | 1.58 |

**Table B.4:** Table with the measurements of the circumference of the trees measured at an area of 100m$^2$ around the sample plot of the sound measurement. All trees were measured at DBH with a measuring clamp.

| ID | Circumference stem (cm) | Area stem ($m^{-2}$) | Basal area (m²/m²) | Percentage stem |
|---|---|---|---|---|
| AmAsh1 | 94 | 0.070 | 0.0038 | 0.375 |
| | 110 | 0.096 | | |
| | 60 | 0.029 | | |
| | 86 | 0.059 | | |
| | 72 | 0.041 | | |
| | 42 | 0.014 | | |
| | 91 | 0.066 | | |
| AmsAsh2 | 106 | 0.089 | 0.0045 | 0.446 |
| | 127 | 0.128 | | |
| | 53 | 0.022 | | |
| | 132 | 0.139 | | |
| | 46 | 0.017 | | |
| | 52 | 0.022 | | |
| | 60 | 0.029 | | |
| Cherry1 | 86 | 0.059 | 0.0024 | 0.243 |
| | 60 | 0.029 | | |
| | 90 | 0.064 | | |
| | 70 | 0.039 | | |
| | 81 | 0.052 | | |
| Cherry2 | 86 | 0.059 | 0.0033 | 0.334 |
| | 96 | 0.073 | | |
| | 78 | 0.048 | | |
| | 90 | 0.064 | | |
| | 32 | 0.008 | | |
| | 77 | 0.047 | | |
| | 65 | 0.034 | | |
| Lime1 | 69 | 0.038 | 0.0040 | 0.400 |
| | 111 | 0.098 | | |
| | 55 | 0.024 | | |
| | 109 | 0.095 | | |
| | 101 | 0.081 | | |
| | 90 | 0.064 | | |
| Lime2 | 101 | 0.081 | 0.0029 | 0.294 |
| | 126 | 0.126 | | |
| | 50 | 0.020 | | |

**Table B.4 continued from previous page**

| ID | Circumference stem (cm) | Area stem ($m^2$) | Basal area per plot ($m^{2\ -2}$) | Percentage stem per plot |
|---|---|---|---|---|
| | 37 | 0.011 | | |
| | 60 | 0.029 | | |
| | 58 | 0.027 | | |
| Maple1 | 118 | 0.111 | 0.0064 | 0.641 |
| | 131 | 0.137 | | |
| | 55 | 0.024 | | |
| | 136 | 0.147 | | |
| | 75 | 0.045 | | |
| | 101 | 0.081 | | |
| | 110 | 0.096 | | |
| Maple2 | 60 | 0.029 | 0.0033 | 0.328 |
| | 83 | 0.055 | | |
| | 115 | 0.105 | | |
| | 70 | 0.039 | | |
| | 112 | 0.100 | | |
| Beech1 | 104 | 0.086 | 0.0028 | 0.280 |
| | 91 | 0.066 | | |
| | 127 | 0.128 | | |
| Beech2 | 161 | 0.206 | 0.0078 | 0.783 |
| | 126 | 0.126 | | |
| | 161 | 0.206 | | |
| | 175 | 0.244 | | |
| NROak1 | 120 | 0.115 | 0.0036 | 0.358 |
| | 51 | 0.021 | | |
| | 145 | 0.167 | | |
| | 47 | 0.018 | | |
| | 35 | 0.010 | | |
| | 35 | 0.010 | | |
| | 48 | 0.018 | | |
| NROak2 | 157 | 0.196 | 0.0055 | 0.549 |
| | 40 | 0.013 | | |
| | 44 | 0.015 | | |
| | 119 | 0.113 | | |
| | 32 | 0.008 | | |
| | 69 | 0.038 | | |
| | 105 | 0.088 | | |
| | 99 | 0.078 | | |