Quantifying scattered sound energy from a single tree by means of reverberation time

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ABSTRACT

Trees in urban spaces surrounded by buildings may be effective in dispersing sound energy, and this could affect sound level distribution and street canyon reverberation. To quantify this effect of trees with a view to including it in numerical predictions, this paper examines sound scattering from a single tree in open field by means of reverberation time (RT). Five trees of different species and crown sizes were considered. The influence of ground condition, receiver height, crown size and shape, foliage condition, and source-receiver angle and distance has been assessed. The results show that RT20 is proportional to the tree crown size, which is the most important factor. The maximum RT20 measured was 0.28 sec at 4000 Hz for the studied trees when in leaf (with foliage). The presence of leaves increased RT20 at high frequencies, typically by 0.08 sec at 4000 Hz. It was also demonstrated that the source-receiver angle can affect the characteristics of decay curves significantly. With increasing source-receiver distance within 40 m, RT20 was slightly changed. It was shown that ground condition and receiver height affect the decay curves, especially at low and mid frequencies, where sound scattering is of relatively limited importance.

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I. INTRODUCTION

In the last few decades since the pioneering work by Eyring[1] in 1946, studies on the acoustic effect of trees have been focused on sound propagation through forests and tree belts. A number of studies have demonstrated the effect of forests and tree belts on noise reduction[2-7]. Various numerical and experimental methods have also been investigated to characterize the influential factors affecting sound propagation through forests. Previous work suggests that ground effect, sound scattering, and sound absorption by tree elements (trunks, branches, stems, leaves, etc.) play a significant role in sound propagation through forests[8-21]. Ground effect is the result of interference between direct sound and sound reflected from the ground. It depends on the acoustic properties of the ground, as well as the positions of the source and receiver. At frequencies above 1 kHz, trees contribute to sound attenuation increasingly with frequency due to sound scattering by trunks and branches, as well as foliage scattering and absorption by viscous friction and damped vibrations. There have also been a few attempts to show that forests induce a reverberant sound field, indicating the importance of sound scattering by tree elements[22-24].

While there have been numerous studies involving groups of trees, it is also worth examining sound scattering by a single tree. Firstly, this helps validate theoretical models for predicting sound propagation through forests. Secondly, in reverberant urban spaces such as street canyons and courtyards, trees are expected to influence sound field characteristics including RT (reverberation time) and sound level distribution. Compared to open field, the effect of trees could even be enhanced since there are multiple passages through the trees due to multiple reflections between building façades[25-27]. Thus, information on sound scattering from a single tree would be useful for better understanding acoustic effects of trees in these urban environments.

The aim of this study is therefore to investigate the effect of a single tree in open field on sound scattering by means of RT, and to examine which parameters are relevant. The effect of a single tree on sound scattering is expected to depend on many factors such as the tree canopy size and species, the amount and seasonal condition of foliage, source-receiver angle and distance, ground condition, and source and receiver heights. Consequently, a series of field measurements involving five single trees of different species and crown sizes were carried out.

II. PRINCIPLE OF QUANTIFYING SCATTERED SOUND ENERGY FROM A SINGLE TREE BY MEANS OF REVERBERATION TIME

As shown in Fig. 1, sound propagating near a single tree can arrive at a receiver by a number of paths, including direct sound, ground reflected, purely scattered, and scattered in combination with ground reflection. This shows complex mechanisms of sound scattering produced by a single tree.

Fig. 2 shows two impulse responses measured in open field in the presence and absence of a single tree (Tree 5 in Fig. 3). The measurement was carried out at a source-receiver distance of 60 m for a point source (starting pistol) at 1.5 m height and a receiver at 1.5 m height. The result with the tree has considerably stronger sound energy in the late part of the impulse response in comparison with the result without the tree. Correspondingly, this would bring an increase in RT.

III. MEASUREMENT METHOD

A. Experimental conditions

Measurements were carried out six times in the Park at Chatsworth House near Sheffield, United Kingdom, between September 2010 and March 2012. Five individual trees of different species and sizes were selected to examine the importance of sound scattering (see Fig. 3).

To suppress late reflections, the selected trees stood alone on flat grassland with sufficiently large distances (over 70 m) to other trees and obstacles. The sound scattered by a targeted tree decays 35 dB from the initial amplitude within 150 ms, or 51 m assuming a sound speed of 340 m/s. Therefore, a maximum source-receiver distance of 60 m was determined to provide a sufficient time interval between scattered sound from a tree and late reflections from other obstacles.

Table I describes properties of the five individual trees named from Tree 1 to Tree 5 on the basis of increasing size. The areas of imaginary surfaces enclosing the tree crowns, with their complex shapes, were calculated using Google's SketchUp programme with a function to adjust scale on the basis of a reference object (i.e. a human figure in this study). Table II provides meteorological conditions during the measurements. Humidity and temperature were measured 1.5 m above the ground with a CEM DT-615 meter just before and after each set of acoustical measurements. Wind speed 2.5 m above the ground was recorded with a Testo 405-V1 meter at the same times. Temperatures and relative humidity levels were quite similar during the measurements, except on Days 2 and 6. This inconsistency might have caused different atmospheric absorption especially at high frequencies due to the rather long travelling path in a tree crown. However, the atmospheric attenuation coefficient α (dB/m) at 4000 Hz for each measurement day, calculated based on ISO 9613-1[28], indicates that the difference in temperature and humidity has a negligible contribution to the variation in scattered sound for the considered distances. The wind speed was less than 4 m/s, implying low background noise by wind and the rustling of leaves. This has been confirmed by checking INR (impulse-to-noise ratio). In Fig. 3, the condition for each tree with foliage is shown.

B. Measurement setup

A similar measurement methodology was used as reported before in the work by Ding *et al.*[29]

Shots from a starting pistol were used as acoustic excitation. Five consecutive shots were released and the results averaged out, yielding a sufficient reproducibility for this type of sound source[30]. The recording systems comprised 1/2” microphones (BSWA MP 231 and G.R.A.S. MCE 201) and preamplifiers (BSWA MA231T and 01dB-Stell Pre 12H) connected respectively to a 4-channel Edirol R-44 recorder and a 2-channel 01dB Symphonie unit. Sampling frequency and bit depth for both systems were 48 kHz and 24-bit.

Fig. 4 shows the cross-section and top-view of the measurement condition, where the source and receiver distance from a tree trunk is represented as d_s and d_r, respectively, while h_s and h_r are the heights of the sound source and receiver. The source-receiver angle is defined with $\theta_{s\text{-}r}$, indicating the difference in angle between d_s and d_r. Therefore, $\theta_{s\text{-}r}=180$ degrees means a straight sound propagation path connecting source, trunk and receiver.

IV. VALIDATION OF MEASUREMENT AND DATA ANALYSIS METHODS

A. Data analysis method

In this study, RT based on the impulse responses recorded from the field measurement was analyzed using the DIRAC programme from B&K[31]. RT is derived from the decay curve between 5 dB and 15, 25, 35 dB below the initial level. From the corresponding slope, T10, T20 and T30 are calculated as the times to reach -60 dB relative to the initial level. EDT (early decay time), derived from the decay curve between 0 dB and 10 dB below the initial level, is an inadequate descriptor to evaluate the scattered sound from trees as there is relatively weak energy in comparison with a direct sound. DIRAC has the time reversed filtering function to enable accurate measurement of very short RT which is needed for this study.

B. Impulse response to noise ratio

The INR is an important parameter, providing information about the quality of the measurement for RT. It is defined as the ratio of the maximum impulse response level and background noise level, reflecting the decay range. According to ISO 3382-2[32], the INR should be at least 35 dB and 45 dB for accurate measurement of T20 and T30, respectively.

At the source-receiver distance of 60 m (d_r=30 m, d_s=30 m, $\theta_{s\text{-}r}$=180 degrees), the INR measured for Tree 2 on Day 3 was 22.2±2.2 dB at 63 Hz, 36.8±2.8 dB at 125 Hz, 45.0±2.7 dB at 250 Hz, 48.8±2.5 dB at 500 Hz, 48.4±2.9 dB at 1000 Hz, 56.6±1.5 dB at 2000 Hz and 54.0±2.5 dB at 4000 Hz. The standard deviation indicates the variation in the INR for five consecutive pistol shots. The maximum standard deviation of 2.9 dB at 1000 Hz suggests that the measurement method using starting pistol shots is reliable. The result suggests that the INR is sufficiently high to calculate T10 and T20 for source-receiver distances within 60 m, which is the maximum source-receiver distance considered in this study. However, it can be seen that the INR at some frequencies including 63 Hz, 125 Hz and 250 Hz is insufficient to calculate T30. Therefore, it is appropriate to use T10 or T20 in terms of data reliability although the INR at 63 Hz is still insufficient for calculating T20.

C. Determination of RT

In Fig. 5, decay curves in octave band frequencies from 125 Hz to 4000 Hz are shown for sound propagating in the presence and absence of Tree 3 with foliage. In this measurement, the source and receiver were positioned at d_s=10 m, d_r=10 m, h_r=0.2 m, h_s=0.2 m and $\theta_{s\text{-}r}$=180 degrees. The measurement without the tree was carried out at the same conditions, except with a slightly different source-receiver distance of d_s=13 m and d_r=13 m which has a negligible contribution to the variation in RT. The result for open field without the tree indicates that RT at low frequency is rather long, mainly because of the filters applied during the post-processing of the time responses. This cannot be avoided, and thus some ghost RT that has no physical meaning will always be measured at very low frequencies. However, the filter effect induces negligible ghost RT for T10 and T20 less than 0.02 sec. On the other hand, decay curves in the presence of Tree 3 show that above 1000 Hz, trees clearly introduce reverberation. It is also noticeable that weak scattering sound at 500 Hz is produced after -25 dB below the initial level, which can cause significant variation in RT with different decay ranges, especially for T30.

Fig. 6 shows RT with the three different decay ranges for the decay curves in Fig. 5. The standard deviation in Fig. 6 indicates the variation in RT for five consecutive pistol shots. The result for the presence of Tree 3 shows that RT generally increases with increasing frequency. This corresponds with prior knowledge that sound energy is more effectively scattered by vegetation and trees at high frequencies than at low frequencies, yet RT remains less than 0.2 sec. It is noticeable that T30 at 500 Hz is considerably different from T10 and T20 due to weak scattering of the direct sound but relatively important sound levels arriving after 10 ms. RT measured in open field suggests that the DIRAC programme is accurate for calculating impulse responses with very short RT although T30 is slightly longer compared to T10 and T20. It is also noted that RT at low frequencies is not caused by the tree because the results with and without the single tree are similar. In this study, therefore, the decay range for T20 is used to investigate the sound scattering effect of a single tree.

D. Repeatability of the measurement method

Repeatability of the measurement method was examined on Day 3 and Day 4, with a 12 day interval. The temperature and humidity on both days were rather similar, as can be seen in Table II. The measurement was carried out for Tree 2 with foliage at the source-receiver distance of 20 m (d_r=10 m, d_s=10 m). The measurement condition for source and receiver was h_r=0.2 m, h_s=0.2 m and $\theta_{s\text{-}r}$=180 degrees. It was estimated that the maximum difference in

RT20 between the two days is 0.03 sec at 500 Hz, which indicates the repeatability of the measurement and analysis methods.

To examine uniformity of sound scattering, RT20 for the six straight lines ($\theta_{s\text{-}r}$=180 degrees) with 60 degrees interval, meaning one rotation in reference to the tree trunk, was measured for Tree 2 with foliage. The source-receiver distance and height were the same as described above. The maximum difference in RT20 between the results measured at the six different straight lines positions was 0.02 sec. Thus, Tree 2 can be considered as a uniform scatterer in the horizontal plane. It is expected that other trees could also scatter sound uniformly as the canopies are approximately symmetric.

E. Ground conditions and receiver heights

Differences in ground conditions can affect RT20 due to the variation in the amplitude of reflected sound. Although field measurements were carried out at the same source and receiver configurations, the ground condition for each tree could be different due to many factors such as root structure, soil composition, moisture content, and seasonal influences. Therefore, it is necessary to investigate the effect of ground condition on sound scattering. For this, the decay curve for grassland (assumed as soft ground) is compared with that for three different ground conditions using 2 mm thick hard plastic panels covering the source-receiver line from the tree trunk. The four different ground conditions were: (1) bare grassland all around the tree, (2) 11 m long by 2 m wide hard cover on the receiver *R* side, (3) 11 m long by 2 m wide hard cover on the source *S* side, (4) these hard covers on the *S* and *R* sides simultaneously. The measurement was conducted for Tree 2 on Day 6 with d_r=10 m, d_s=10 m and $\theta_{s\text{-}r}$=180 degrees. The effect of receiver height on the decay curve was also examined at h_r=0.2, 1.5, 3.0 and 4.0 m with the same source height of h_s=0.2 m. In Fig. 7, decay curves with the different ground conditions at the receiver height of 0.2 m for Tree 2 are shown from 500 Hz to 4000 Hz.

The result in Fig. 7 indicates that the different ground conditions play an important role in the characteristics of the decay curves, especially at 500 Hz and 1000 Hz. At 500 Hz, in comparison with soft grassland, the amplitude near 10 ms with the hard ground on the receiver side is rather high. At 1000 Hz, relatively strong sound energy for soft ground near the receiver can be found at rather late parts of decay curves in comparison with hard ground. At higher frequencies, on the other hand, the variation in the characteristics of the decay curves with different ground conditions is insignificant. This is consistent with the fact that ground effects, averaged over full-octave bands, are not present anymore[33] at these frequency bands. Hard ground on the source side seems to have less influence. This lack of reciprocity remains unexplained.

Fig. 8 shows the effect of the ground conditions and receiver heights on RT20 for Tree 2. The standard deviation again indicates the difference in RT20 for five consecutive pistol shots. The result in Fig. 8 shows that the different ground conditions produce variations in RT20 at all receiver heights, especially at 500 Hz and 1000 Hz for the considered source-receiver geometry, while there is an insignificant difference in RT20 at lower and higher frequencies. The results also show that receiver heights can affect the variation in RT20 at certain frequencies.

V. MEASUREMENT RESULTS

A. Effects of tree size with and without foliage

The trees considered in this study have five different heights between 7.7 m and 20.6 m. The diameters of the five tree crowns are between 6.9 m and 21.5 m. To examine the effect of tree crown size on scattered sound energy, measurements were carried out with a source-receiver distance of 20 m (d_r=10 m, d_s=10 m) and $\theta_{s\text{-}r}$=180 degrees for the five trees with and without foliage. The height of both source and receiver was 0.2 m. The measurements for the five trees with and without foliage were carried out on Day 3 and Day 5, respectively. For the five trees with foliage, Fig. 9 shows the decay curves in octave band frequencies from 500 Hz to 4000 Hz. Decay curves at low frequencies are not shown here because there is insignificant sound scattering by the trees.

The result in Fig. 9 indicates that the RT20 proportionally increases with increasing size of the trees because a larger tree produces relatively stronger sound scattering and longer sound paths through the crown. Above 500 Hz, it can be seen that the characteristics of decay curves significantly depend on the tree size. For relatively small trees like Tree 1, Tree 2 and Tree 3, the scattered sound energy at 500 Hz is weak relative to direct sound. The results at high frequencies show that the slope of decay curves is rather linear with a slow decrease of sound energy. The decay time at 4000 Hz for Tree 4 is approximately 120 ms at -25 dB below the initial level, indicating long travelling paths in the tree crown.

Fig. 10 shows RT20 according to the surface area of the trees with and without foliage in octave band frequencies from 500 Hz to 4000 Hz. Above 500 Hz, RT20 is gradually increased with the increasing surface area of the trees. The maximum RT20 is 0.26 sec at 4000 Hz for Tree 4 with foliage. It is noted that the RT20 at 4000 Hz is decreased above around 200 m^2. This was because a large number of leaves on Tree 5 were fallen on Day 3 due to the season, as shown in Fig. 3. However, the result from another measurement, obtained on Day 1, indicates that RT20 at 4000 Hz can reach 0.28 sec when Tree 5 is in full leaf. It can also be seen that single trees without foliage can contribute to the increase in RT20 with increasing tree crown size. Compared to the trees with foliage, RT20 for the relatively small trees (Tree 1, Tree 2 and Tree 3) without foliage is higher at 500 Hz and 1000 Hz due to different ground conditions between Day 3 and Day 5. Since the sound source is low ($h_s = 0.2$m), interference patterns only appear for relatively high frequencies, i.e. above 500Hz. Thus, this leads to some important uncertainties in the analysis of the effect of trees without and with foliage due to different ground conditions.

The leaves on the five single trees studied here have widths and lengths below 15 cm. This size corresponds to the wavelength of sound at 2250 Hz, and thus it is expected that foliage has an influence mainly on sound scattering at or above this frequency. At 4000 Hz, it is shown that RT20 for trees with foliage is higher than those without foliage. In particular, RT20 by Tree 4 is increased by 0.08 sec in the presence of foliage, confirming that foliage scattering occurs at high frequencies. As for Tree 5, RT20 at 4000 Hz can be increased by 0.08 sec when in full leaf. Overall, the results indicate that leaves increase RT20 at high frequencies. The size and thickness of leaves as well as LAI (Leaf Area Index) and LAD (Leaf Area Density) could also play a role, but this was not studied here.

B. Source-receiver angle

The characteristics of decay curves are influenced by source-receiver angle ($\theta_{s\text{-}r}$) (see Fig. 4). In this study, the effect of source-receiver angle on the decay curve is examined using Tree 2 without foliage on Day 2. The measurement condition was d_s=13 m, d_r=13 m, h_s=1.5 m and h_r=1.5 m. The source-receiver angles were 0, 90, 135 and 180 degrees. The source-receiver angle of 0 degrees was used to estimate the back scattered sound energy (or reflection), which was measured with d_s=40 m and d_r=10 m arranged in a line without the tree between the source and receiver.

In Fig. 11, the decay curves for Tree 2 without foliage with different source-receiver angles are shown at different frequencies. The result shows that decay curves for the source-receiver angle of 135 degrees (45 degrees in reference to 180 degrees) is similar to that for 180 degrees. This is because the time interval between direct and scattered sound is very short for both source-receiver angles due to the relatively close receiver distance from the edge of the tree crown. For the source-receiver angle of 90 degrees, there is a plateau between direct and scattered sound with the time interval of approximately 15 ms (5.1 m for a speed of sound of 340 m/s). This is caused by the difference in distance for the direct sound path (18.4 m) with scattered sound paths (21.5m ~ 26.0 m) from the edge of the crown and the trunk. The decay curve for the source-receiver angle of 0 degrees (back scattering) suggests that the tree can reflect sound energy backwards effectively. It can be seen that there is a pronounced plateau with the time interval of approximately 50 ms (17.0 m) between direct and reflected sound, which indicates strong reflection from the vicinity of the tree trunk. The relative SPL vs time in Fig. 11 suggests that Tree 2 without foliage can reflect sound at frequencies above 250 Hz. In summary, the source-receiver angle can affect characteristics of the decay curve significantly, especially for 0 degrees and 90 degrees. Calculation of RT20 is omitted here due to the long time interval between direct and reflected sound.

C. Source-receiver distance

Measurements for the five individual trees with foliage on Day 3 were conducted to investigate the effect of source-receiver distance on RT20. Values for d_s (source-trunk distance) were 10 m, and for d_r (receiver-trunk distance) 5, 10, 20 and 30 m. The source, tree and receiver were arranged in a straight line with $\theta_{s\text{-}r}$=180 degrees. Therefore, the range of source-receiver distances was between 15 m and 40 m. The height of the source and receiver was 0.2 m. Fig. 12 presents RT20 measured with d_s =10 m for different frequencies as a function of d_r=5, 10, 20, 30 m. At 125 Hz and 250 Hz, RT20 is under 0.03 sec and independent of source-receiver distance. It can be seen that the source-receiver distance plays an insignificant role on RT20 above 500 Hz, except in the case of Tree 5. The variation in RT20 for Tree 5 might be due to the relatively thick trunk and low leaf density, and measurement locations slightly deviating from the straight line between source and receiver. Therefore, it can be concluded that the different source-receiver distances studied here have an insignificant effect on the variation in RT20.

VI. DISCUSSION AND CONCLUSIONS

This study has shown that sound scattering is a significant aspect of the interaction between sound waves and trees. This effect is quantified by means of decay curves, closely linked to the RT, as influenced by the ground condition, receiver heights, tree crown shape and size, the amount and condition of foliage, and source-receiver angle and distance. Repeatability for the measurement using a starting pistol has also been confirmed.

The results quantify the amount of scattered sound energy from a single tree at different frequencies. At very low frequencies, below 250 Hz, no difference in RT20 has been found compared to the same measurement setup and post-processing in absence of a tree (open field). At higher frequencies, the amount of scattered sound energy is generally increased with increasing frequency. It has been found that tree crown size is the most important factor in relation to scattering of sound energy. With increasing surface area of the crown (area of an enclosing surface), RT20 is increased up to 0.28 sec at 4000 Hz. A tree without foliage also produces a similar amount of scattered sound energy as a tree with foliage. Presence of leaves increases RT20 starting from 2000 Hz, by 0.08 sec at 4000 Hz. The characteristics of decay curves are significantly influenced by source-receiver angle, especially for 0 and 90 degrees. Back scattering (or reflection) from a tree has also been observed at frequencies above 250 Hz. It has been observed that distance between source and receiver (within 40 m) under the same angle has insignificant effect on the variation in RT20. Ground condition can contribute to the variation in decay and RT20 at certain frequencies depending on the tree size and source-receiver geometry. However, for the source-receiver geometry of this study the effect is important especially at low and mid frequencies where sound scattering is of relatively limited importance.

Although many field measurements have been carried out in this study, further work is still needed to characterize the effect of other factors such as leaf size, leaf shape and thickness, but also the distribution of biomass over the crown, quantified by LAD (Leaf Area Density). Numerical modeling of scattering of sound energy by trees (as initiated e.g. in Refs. 7 and 34), as well as scale modeling could further clarify the physical phenomena involved and allow evaluation of potential applications. A previous study[35] showed only a slight effect (less than 1.5 dB) on sound reduction by the presence of trees in street canyons. On the other hand, trees in street canyons could be significant in RT distribution since a slight increase in the scattering coefficient of building façades reduces street canyon reverberation, as shown in previous studies[36-39]. Thus, it is necessary to suggest effective planting patterns of trees in urban situations to reduce noise levels. Optimization of planting schemes was shown to be essential, e.g. in the context of tree belts (see Ref. 7), to achieve useful noise reduction.

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List of Tables

TABLE I. Dimensional properties of the trees

	Tree 1	Tree 2	Tree 3	Tree 4	Tree 5
Species	Oak (*Q. robur*)	Oak (*Q. petraea*)	Cherry (*P. avium*)	Maple (*A. pseudoplatanus*)	Lime (*T. × europaea*)
Tree height (m)	7.7	9.2	11.5	14.9	20.6
Tree crown diameter (m)	6.9	12.3	15.7	19.5	21.5
Crown surface area (enclosing surface) (m^2)	30	43	88	161	218
Leaf size (cm)	12.0(L) × 7.5(W)	12.0(L) × 7.5(W)	15.0(L) × 6.0(W)	12.0(L) × 15.0(W)	10.0(L) × 10.0(W)
Trunk diameter (m)	0.14	0.40	0.42	0.51	0.56
Distance from ground to bottom of crown (m)	1.9	1.8	1.9	2.0	2.0

TABLE II. Meteorological conditions for each measurement day

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
Date	21st Sep.2010	20th Apr.2011	14th Oct.2011	26th Oct.2011	13th Mar.2012	14th Mar. 2012
Temperature (°C)	20.3	28.2	16.3	15.0	15.6	9.9
Relative humidity (%)	62.0	34.1	65.8	65.1	56.7	74.3
Wind speed (m/s)	<1.0	<1.4	<3.0	<2.3	<2.5	<4.0
Atmospheric attenuation coefficient α at 4000 Hz (dB/m)	0.025	0.031	0.027	0.028	0.031	0.031

List of Figures

FIG. 1. Diagram for sound paths through a single tree from a point source to a receiver

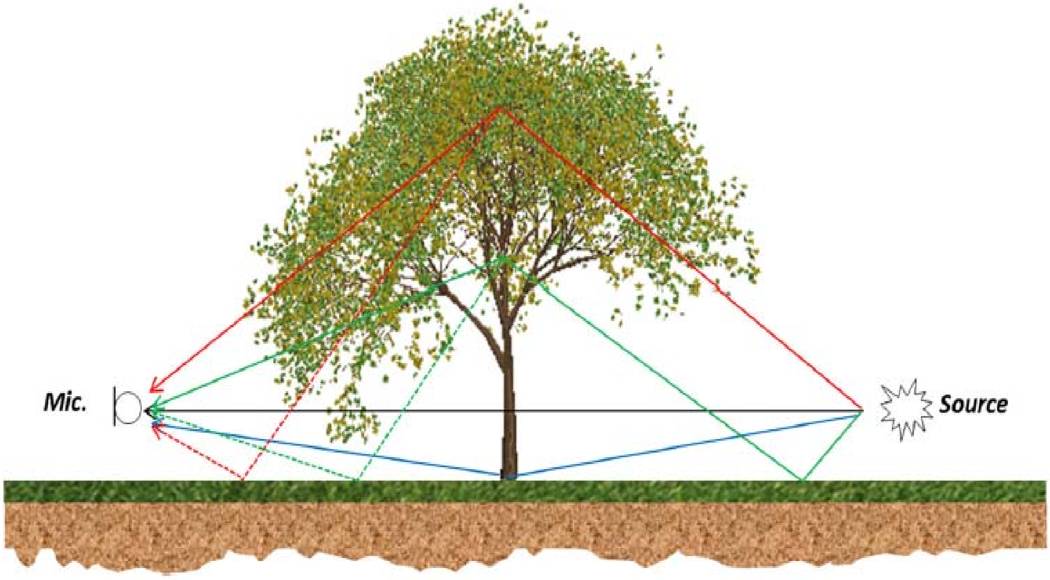


FIG. 2. Impulse responses measured in open field in the absence and presence of a single tree

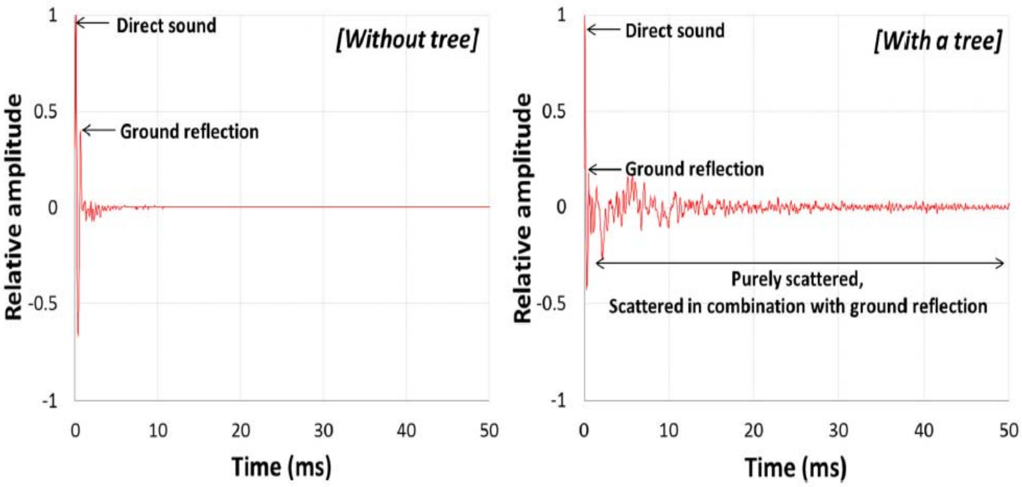


FIG. 3. Conditions for five trees with foliage on Day 3

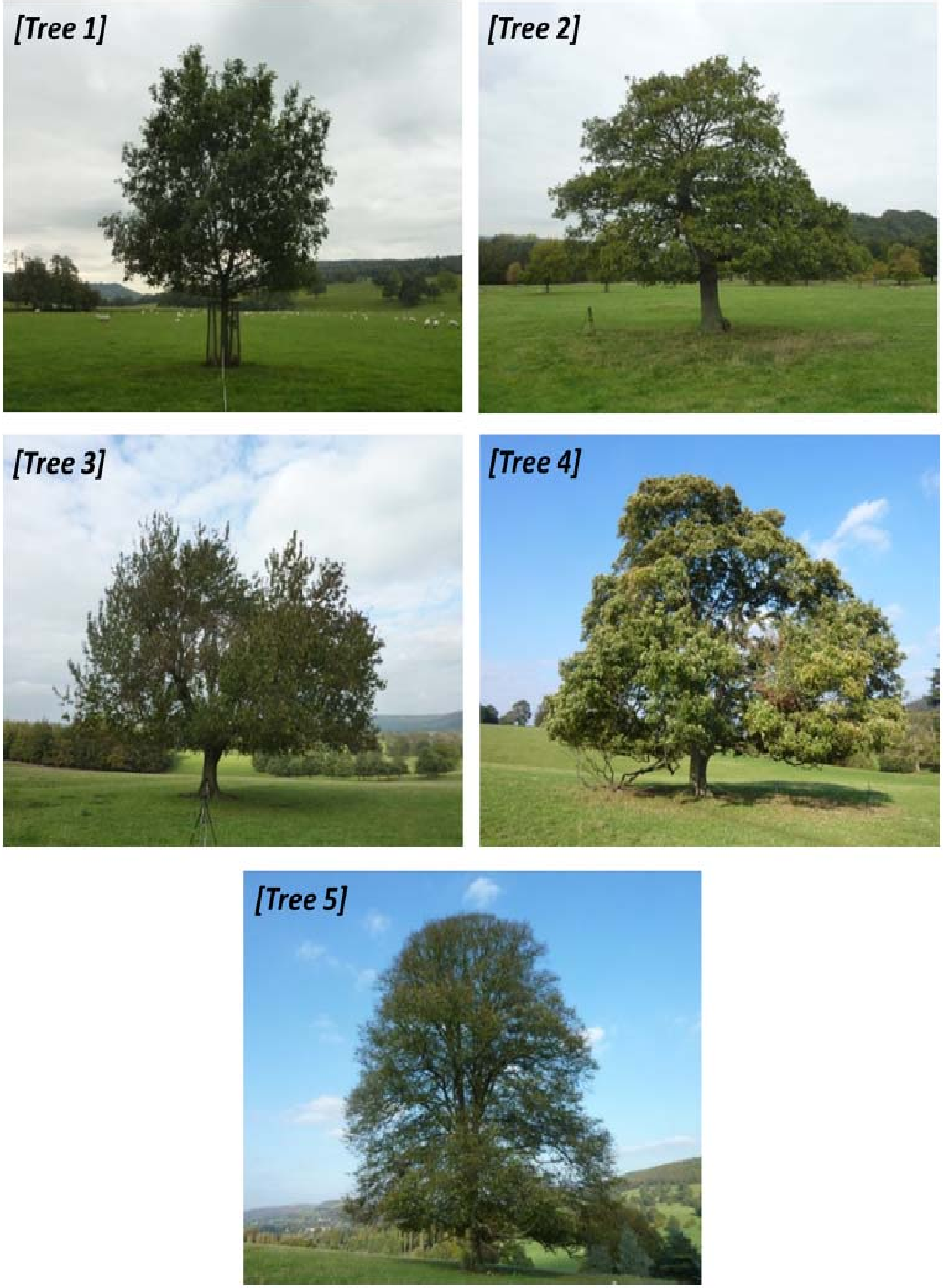


FIG. 4. Cross-section and top-view for measurement conditions, where d_r is the trunk-receiver distance, d_s is trunk-source distance, h_r is the receiver height, and h_s is the source height

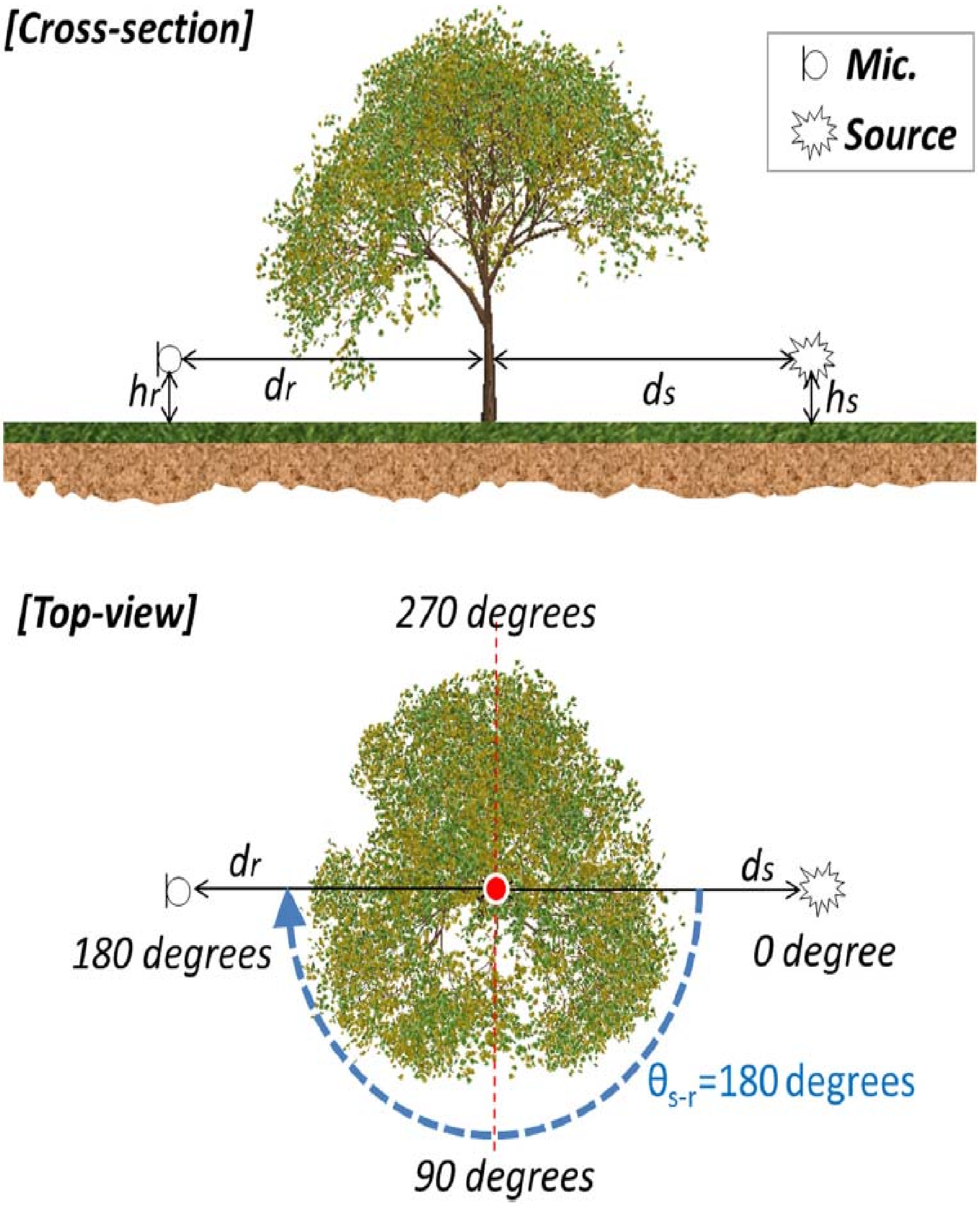


FIG. 5. Comparison of decay curves in the absence and presence of a single tree (Tree 3)

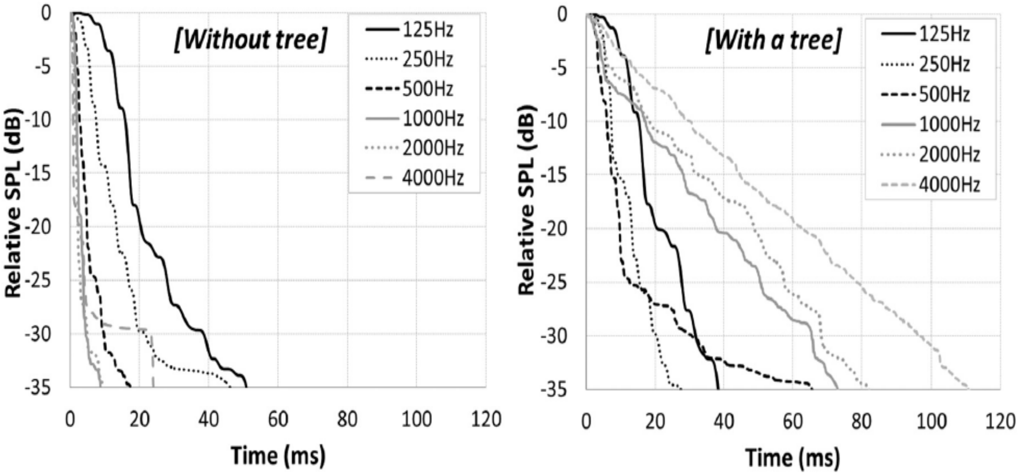


FIG. 6. RT with the three decay ranges corresponding to T10, T20 and T30 in the absence and presence of a single tree (Tree 3)

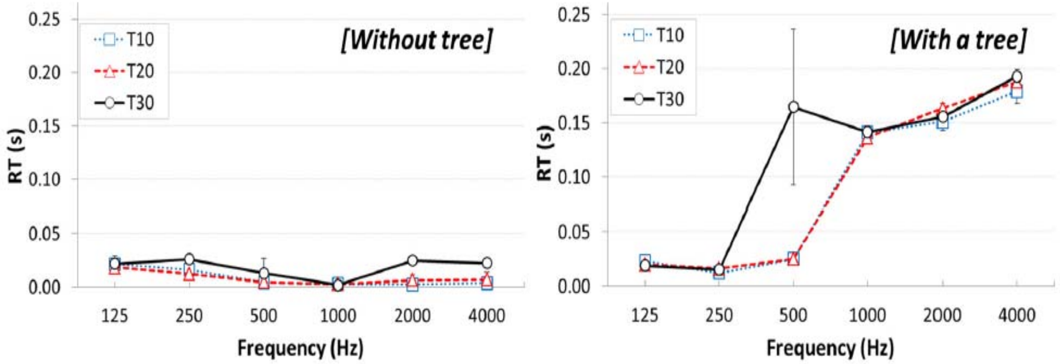


FIG. 7. Decay curves with the four different ground conditions at the receiver and source heights of 0.2 m for Tree 2. Each figure shows the decay curves in octave band frequencies from 500 Hz to 4000 Hz

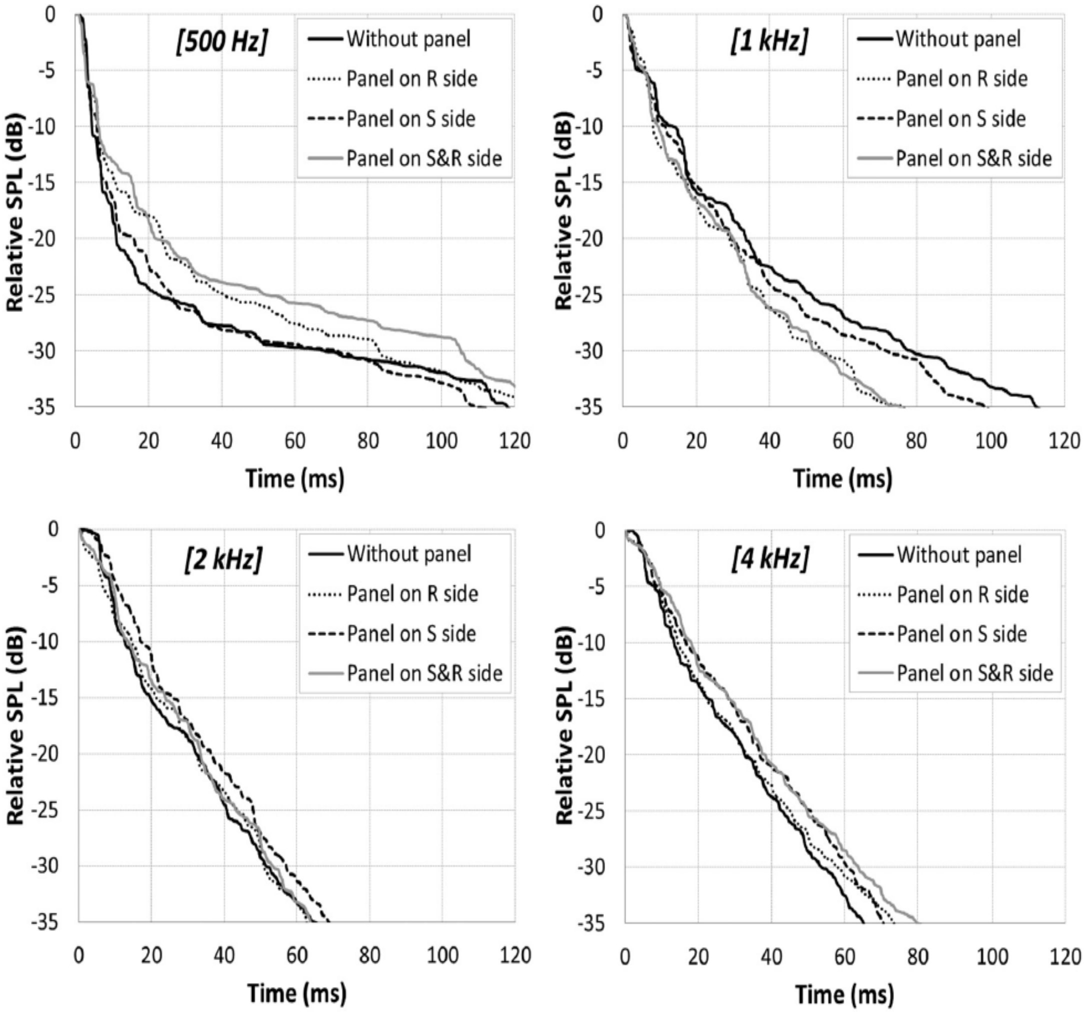


FIG. 8. Effect of the different ground conditions on RT20 for Tree 2 with different receiver heights from 0.2 m to 4.0 m (source height 0.2 m)

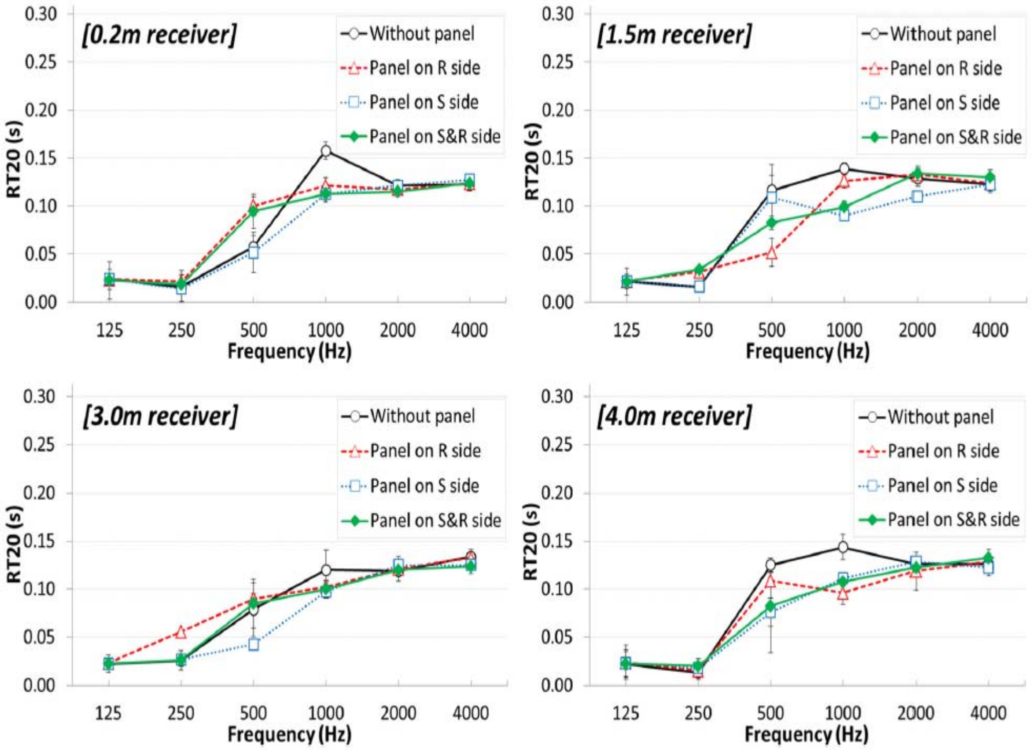


FIG. 9. Decay curves for the five trees with foliage. Each figure shows the decay curves in octave band frequencies from 500 Hz to 4000 Hz

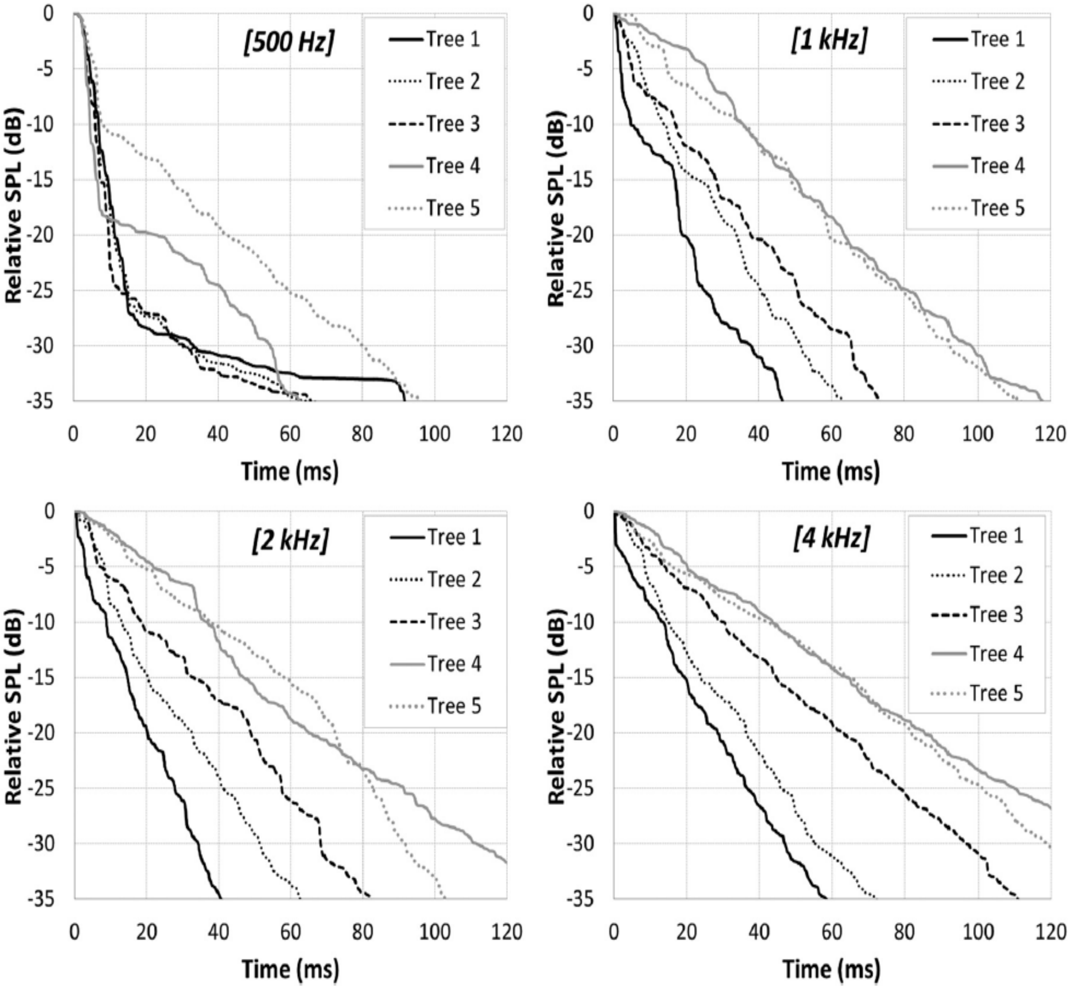


FIG. 10. Effect of the surface area of tree crown with and without foliage on RT20. Each figure shows RT20 in octave band frequencies from 500 Hz to 4000 Hz

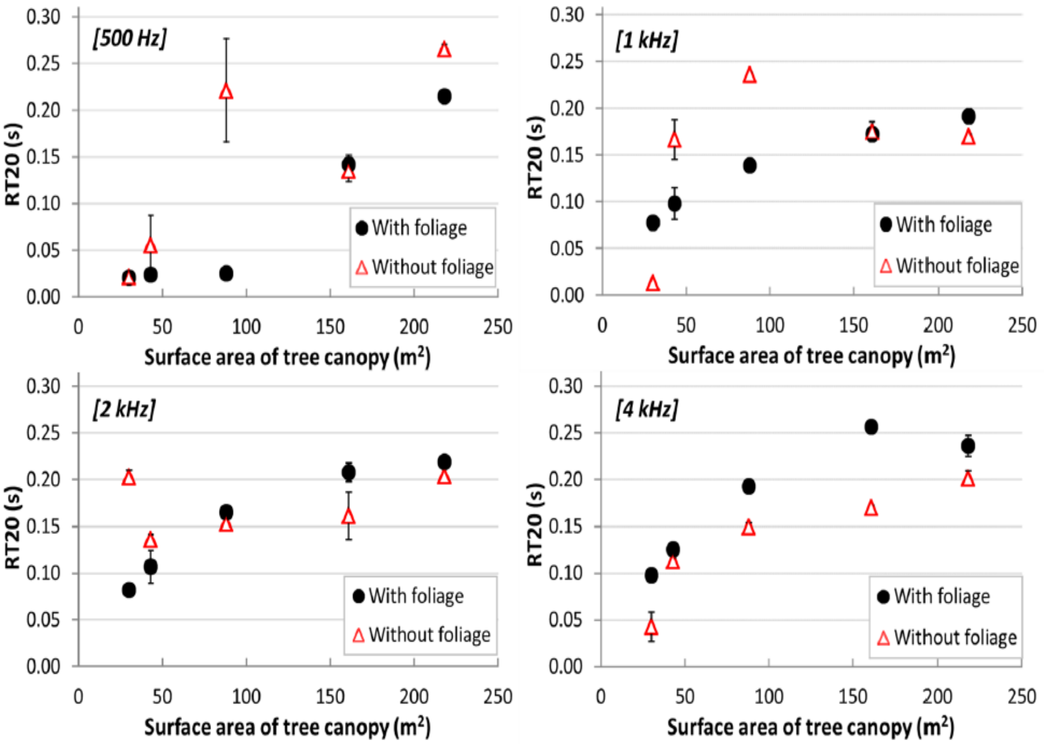


FIG. 11. Decay curves for Tree 2 without foliage with different source-receiver angles. Each figure shows the decay curves in octave band frequencies from 125 Hz to 4000 Hz

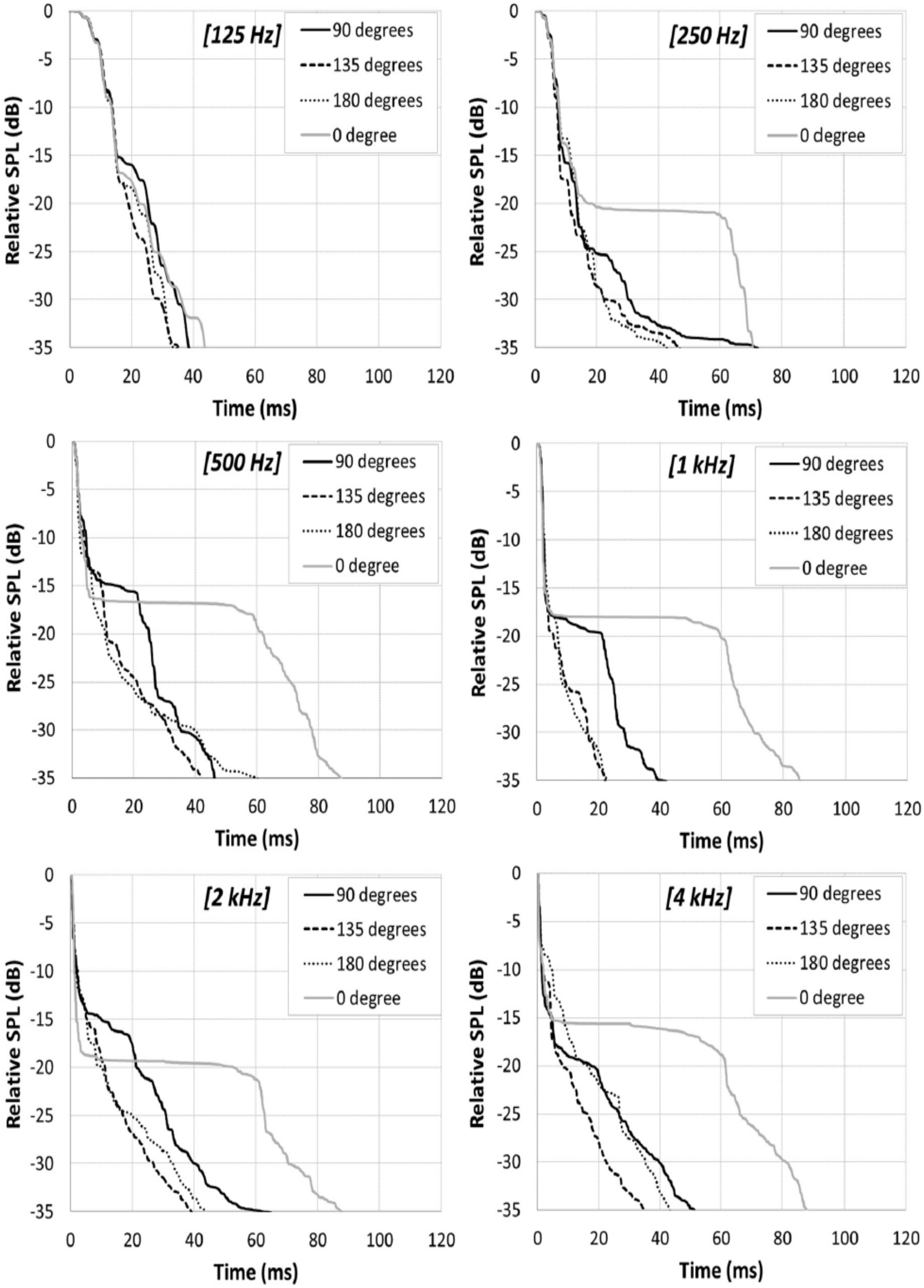
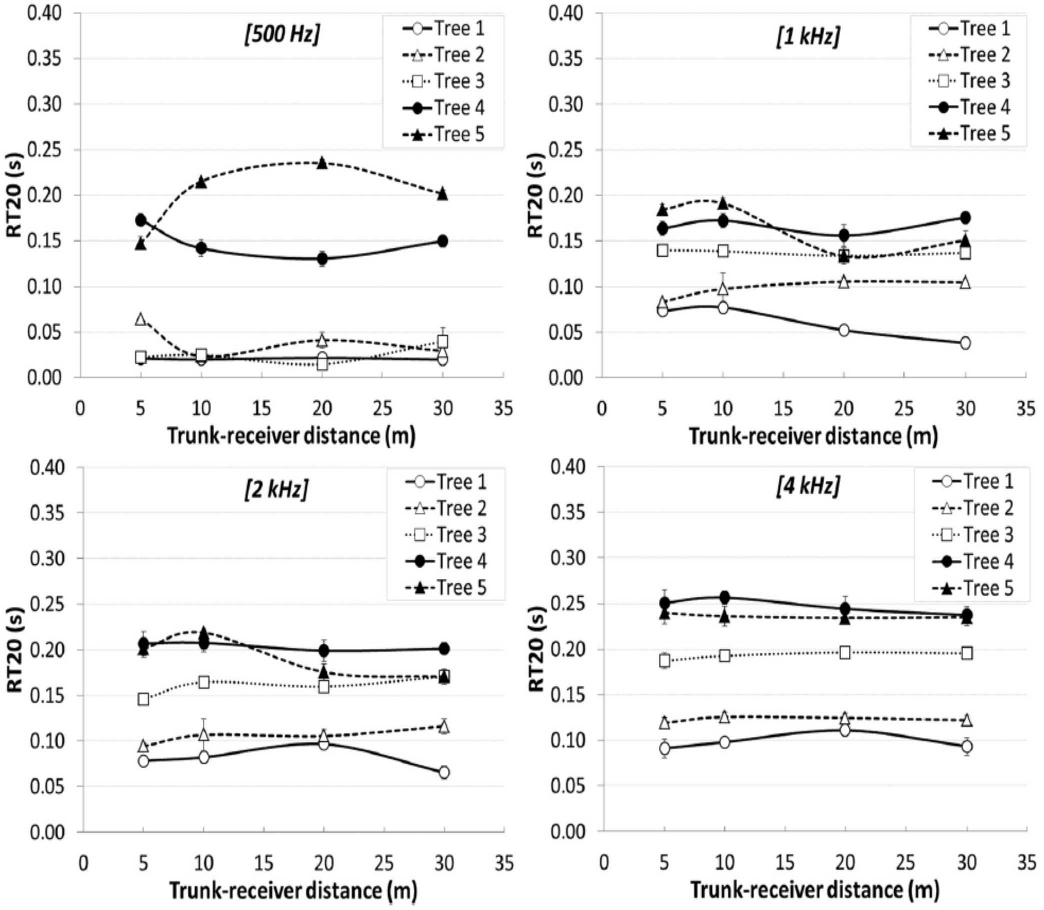


FIG. 12. RT20 with different source-receiver distances from 15 m to 40 m, with d_s=10 m and d_r=5, 10, 20, 30 m for each tree. Each figure shows the decay curves in octave band frequencies from 500 Hz to 4000 Hz


[500 Hz]
[1 kHz]
[2 kHz]
[4 kHz]
Tree 1
Tree 2
Tree 3
Tree 4
Tree 5
RT20 (s)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Trunk-receiver distance (m)
0
5
10
15
20
25
30
35