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Investigation of the noise reduction provided by tree belts

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Abstract

This study investigates the noise reduction effect of 35 evergreen-tree belts. A point source of noise was positioned in front of the tree belts and the noise level at various points in the belts was measured with a noise meter. Factors important for noise reduction include visibility, width, height and length of the tree belts. Stepwise regression was employed to examine the factors associated with noise reduction. A negative logarithmic relationship between the visibility and relative attenuation was found. A positive logarithmic relationship between relative attenuation and the width, length or height of the tee belts was also found. A map showing the relationship between visibility together with width was plotted. The map provides some practical suggestions concerning design of tree belts for noise reduction.

Keywords: Noise reduction; Tree belt

1. Introduction

Vegetation has been proposed as a natural material to reduce noise energy outdoors (Aylor, 1972). There are a few qualitative recommendations regarding principles for design of plantings to reduce noise (Reethof, 1973; Cook and Haverbeke, 1974; Herrington, 1976; Reethof and Heisler, 1976). However, few quantitative data have been reported on the significance of height, density, width and length of tree belts for noise reduction. A model of noise reduction by tree belts was therefore examined in this study. Most earlier studies on noise reduction deal with deciduous and coniferous trees (Embleton, 1963; Aylor, 1972; Cook and Haverbeke, 1974; Kragh, 1979, 1981). Evergreen trees of the subtropics might have somewhat different effects. Furthermore, many earlier studies have only examined tree belts of particular species (Embleton, 1963; Kragh, 1979, 1981), but failed to discuss noise reduction effect in relation to the form of the tree, or the density, height, length and width of the tree belt. Therefore, the noise reduction effect of various broadleaf tree belts was examined in this study. This work was performed in plantations where many complicated variances could be controlled. The tree belt parameters examined included visibility, height, width and length. Subsequently, a noise reduction model was developed, and the results were summarized in a map showing the relationship between noise reduction and both visibility and width.

2. Methods and materials

2.1. Materials

Thirty-five large plantations of single species with a uniform density and height, and an ambient noise

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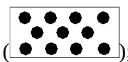
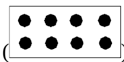
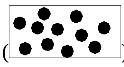
Table 1
The characteristics of the tree belts used in the experiment

Species	Tree belt condition[a]									
	V (m)	*H* (m)	*L* (m)	*W* (m)	ACD (m)	BH (m)	AI (m)	TA[b]	Lca[c]	Map[d]
Bambusa dolichoclada Hayata	1	10	60	70	1.5	0.1	0.1 × 0.2	T	1	◎
Garcinia subelliptica Merr. 1	1.3	4.5	50	20	0.8	0.3	0.5 × 0.5	A	3	◎
G. subelliptica Merr. 2	2.5	6	70	20	1.5	0.2	1.8 × 1.5	A	3	◎
G. subelliptica Merr. 3	3.5	4	70	20	0.7	0.2	0.8 × 08	A	3	◎
G. subelliptica Merr. 4	4.1	4.5	120	20	0.8	0.2	1.4 × 1.4	A	3	◎
F. microcarpa L.f. "Golden Leaves" 1	3	4	110	25	1	0.2	1 × 1	A	3	◎
F. microcarpa L.f. "Golden Leaves" 2	4.5	4	80	30	1	0.2	1 × 1	A	9	◎
F. microcarpa L.f. "Golden Leaves" 3	15.2	4	85	30	2	0.2	3 × 1.5	A	9	◎
F. microcarpa L.f. 4	15	5	50	60	3	0.7	3 × 4	C	8	◎
F. microcarpa L.f. 6	200	5	40	60	3	1.7	3 × 4	A	8	
F. microcarpa L.f. "Hawaii" 5	27.5	3	30	30	1	1	1.2 × 1.2	C	3	
Gardenia jasminoides Ellis.	20	1.5	50	110	1.2	0.2	1.5 × 1.5	C	10	
Nerium indicum Mill.	8.3	4	100	25	1	0.8	1 × 1	R	3	◎
Ilex aquifolium 1	3	2.2	90	55	1.3	0.1	1.3 × 1.3	R	11	
I. aquifolium 2	7	2.2	80	20	1.1	0.1	1.3 × 1.3	R	11	
I. aquifolium 3	15	2.2	50	40	0.4	0.1	0.8 × 0.8	R	11	
I. aquifolium 4	30	1.1	80	150	0.5	0.1	1.5 × 1.5	R	11	
Camellia japonica L.	30	1.8	50	60	1	0.2	1.8 × 1.8	R	2	
Nageia nagi (Thunb) O. Kuntze 1	4.3	4	70	25	1.2	0.1	1.5 × 1	A	2	◎
N. nagi (Thunb) O. Kuntze 2	5	4	110	20	1.2	0.1	1.5 × 1	A	2	◎
N. nagi (Thunb) O. Kuntze 3	7	4	70	20	0.6	0.4	0.7 × 0.7	A	2	◎
N. nagi (Thunb) O. Kuntze 4	10	4	25	20	0.8	0.8	1 × 0.8	A	2	
N. nagi (Thunb) O. Kuntze 5	13	3	30	20	0.5	0.3	1.5 × 1.5	A	2	
Ravenala madagascariensis Sonn.	6.7	9.5	90	30	3	1	1 × 1	R	3	◎
Livistona chinensis (Jacq.) R. Br.	12	4.5	40	45	1	0.7	1 × 1	R	4	
P. formosanum Hayata 1	8.7	7	100	25	1	2.5	1 × 1	C	3	◎
P. macrophyllus 1	11.2	6	30	20	1.5	0.3	2 × 2	C	3	
P. macrophyllus 2	30	5	20	25	1.5	0.3	3 × 3	R	3	
Hibiscus tiliaceus L.	13	4	50	300	1.5	0.1	1.5 × 1.5	R	5	◎
Araucaria heterophylla (Salisb.) Franco.	8	9	70	60	1.5	1	3 × 1.6	C	6	◎
Senna siamea (Lam) H. Irwin & Barneby	12.6	5.5	50	20	0.8	0.3	0.8 × 0.8	R	7	◎
Artocarpus altilis (Parkinson) Fosberg	18.5	7	25	40	1	1.5	1 × 1.5	A	3	
Erythrina variegata L. var *orientalis* (L.) Murr.	25	3.5	30	40	1.2	0.9	1.2 × 1.5	R	8	
Pongamia pinnata (L.) Pierre ex Merr	20	3.5	30	40	0.7	2	0.7 × 0.7	R	8	
P. formosanum Hayata 2	35	2.5	25	15	1.2	2	2 × 1.5	A	3	

[a] *Tree belt condition*: *V*, visibility; *H*, height; *L*, length; *W*, width; ACD, average canopy diameter; BH, bifurcate height; AI, average interval; TA, tree arrangement; Lca, location.

[b] *Tree arrangement*: C, crossing (◎); A, abreast (); R, random (); T, tuffy ().

[c] *Location*: (1) Xhan-xan area, Xin-zhu county; (2) Nan-zhuang village, Xin-zhu county; (3) Tian-wei village, Zhang-hua county; (4)Yan-pu village, Zhang-hua county; (5) Guan-yin village, Tao-Yuan county; (6) Long-tan town, Tao-Yuan county; (7) Zhen-ho village Zhang-hua county; (8) Bei-tou area, Taipei city; (9) Pu-xin village, Xin-zhu county; (10) Qiong-lin village, Xin-zhu county; (11) San-zhi village, Taipei county.

[d] *Map*: Data of these tree belts were adapted to construct a map of visibility and width for noise reduction. The criteria for selection were height ≥4 m and width ≥50 m.

maintained at 48 ± 2 dB A were selected for acoustic measurement. There were 19 species of evergreen trees and shrubs on the plantations. The species and the characteristics of the plantations are given in Table 1. The relative attenuation data obtained from 35 plantations were used for regression analysis. Eighteen plantations selected on the basis of height and length (refer to Section 2.7 for the selection criterion) were further examined. The relative attenuation of the 18 plantations were plotted on a map to establish the relationships among visibility and width of plantation and noise reduction.

2.2. Development of a noise source

City traffic noise was recorded and edited for use as the noise source in this experiment. At first, the traffic noise at a main artery, Sec. 3, Xin Yi Road, Taipei City, was recorded at 17:30–18:30 h on 21 March 2000. The recorded noise was termed as unedited noise source. A 10 s interval of noise which had little fluctuation of sound pressure levels was chosen from the unedited noise source, and the chosen noise was recorded repeatedly on a tape in a professional recording studio (Por Tools software) for 30 min. This recording was termed the edited noise source. The spectrum of the edited noise source is shown in Fig. 1. The sound pressure level range of the edited noise source was 73–77 dB A at a distance of 5 m from the source. The edited and unedited noise sources were measured with a noise meter (01dB-Stell SIP95S) at a distance of 5 m from the source. The sound pressure level of accumulative mean value of the unedited noise source became stable after 112 s, but the edited noise source became stable in 22 s (Fig. 2). The fluctuation of sound pressure level of the edited noise source was smaller than that of unedited noise source. It implies that the mean value of edited noise source can be obtained in a short period. Therefore, in each measurement we measured the sound pressure levels of the edited noise source for 30 s and a stable mean value could be obtained quickly. Finally, 100 measurements (01dB-Stell SIP95S), each lasting 30 s were taken 1 m from the source on open ground. The accumulative mean value of the sound pressure level from the 100 measurements revealed that the mean value approached a fixed value after 10 cycles, implying that measuring the noise 10 times yielded a stable mean value. Thus, measurements were taken 10 times at each measuring site.

2.3. Experimental design

At each tree belt, sound pressure levels were measured at points along two transect lines 2.5 m either side of the center liner which perpendicularly crossed the belt (Figs. 3 and 4). On each transect line, the measuring sites were 5 m apart, starting at the edge of the tree belt, and labeled as 5 m measuring site, 10 m measuring site, 15 m measuring site, and so on. Since the width of the tree belts differed and, hence, the length of transect lines ranged from 15 to 50 m, the number of the measuring sites ranged from 3 to 10 among different tree belts accordingly. The relative sound pressure levels of each measuring site on both transect lines (e.g. of the 5 m measuring site on

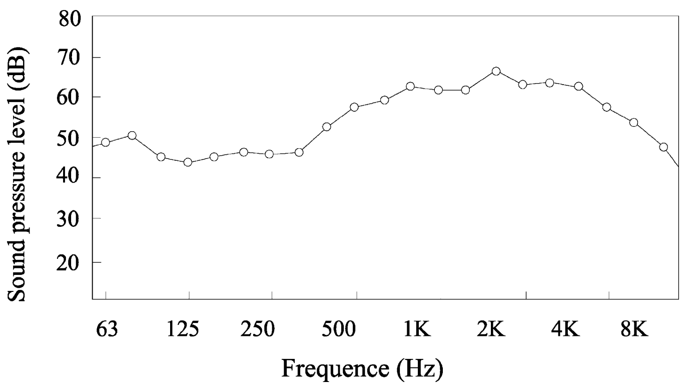


Fig. 1. One-third octave band center frequency at 5 m from the edited noise source.

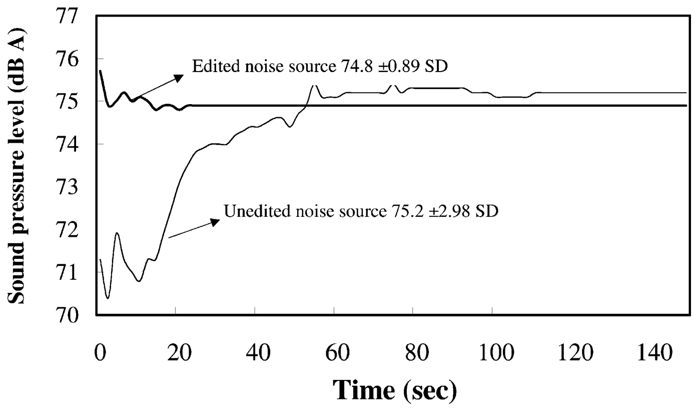


Fig. 2. The accumulative mean value of sound pressure level from the edited and unedited noise source.

transect lines A and B) were averaged to obtain the mean value of that measuring site for each tree belt. Control test runs were set up on open ground near tree belts being tested to compare the difference in sound pressure levels between the tree belts and open ground (Fig. 3).

2.4. Acoustics measurement

The experiments were conducted during June and September 2000. The noise source (AIWA amplifier, 50 W) was placed on each transect at 1 m from the edge of the tree belt and 1.2 m above the ground (Fig. 4)

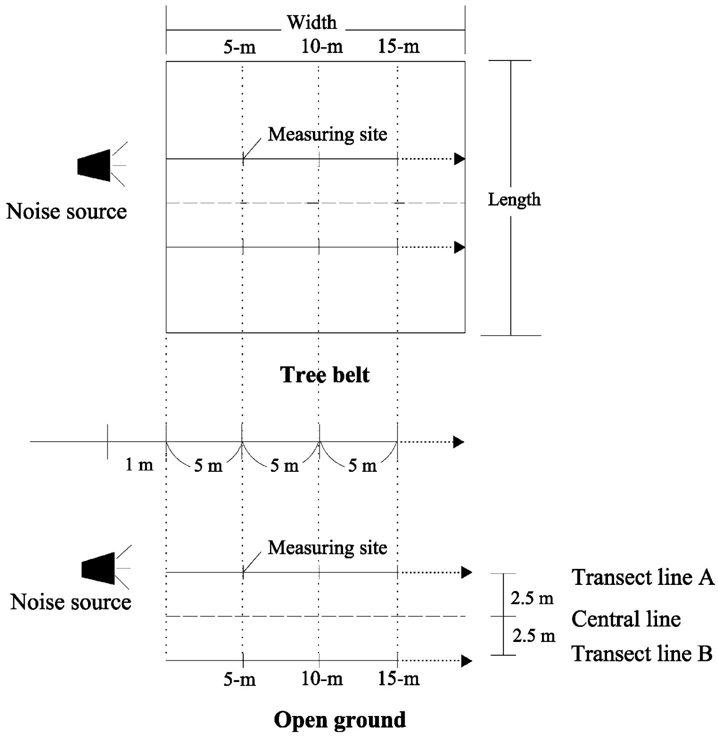


Fig. 3. The experimental design.

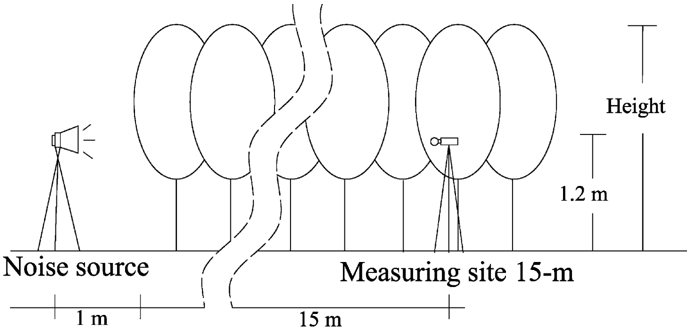


Fig. 4. The profile of experimental design.

as reported by Embleton (1963). The source produced 74.8 dB A of noise measured at 5 m from the source. The sound level meter (01dB-Stell SIP95S) was positioned 1.2 m above the ground at each measuring site and faced the noise source (Fig. 4). The noise meter and amplifier were operated for more than 1 min before the formal measurements were taken. The noise meter was calibrated with a 01dB-CAL01 acoustic calibrator before use. After the apparatus was calibrated, the noise was measured by the noise meter 10 times, 30 s each, at every measuring site. The noise meter was set up using A-weight signal level and fast characteristic time response.

Although climate influences the velocity of sound propagation, Embleton (1963) ascertained that the molecular absorption was slight and the effects due to climate can therefore be neglected when weather conditions are similar. Therefore, measurements were conducted under the same specific weather conditions to eliminate the effect of climate on the results (Embleton, 1963; Cook and Haverbeke, 1974). To increase the accuracy of this experiment, observations were made at wind velocities of less than 2 m/s and during sunny periods. In order to demonstrate the repeatability of this study, the measurement of 35 tree belts were repeated after 1–5 weeks with the same climate conditions. The results shows that the maximum differences of two measurements were within ±10% of each other.

2.5. Measurements of tree belts

The density of tree belts is difficult to measure. Some investigations have used visibility, that is, the distance that an object is obscured by the vegetation as a surrogate for density (Eyring, 1946; Embleton, 1963).

This study measured visibility on the two transect lines according to the method of Eyring (1946) and Embleton (1963). One individual stood in front of the tree belt and another individual walked straight into the tree belt on the transect line until the individual on the edge could no longer see him. The distance between the two members when the second individual disappeared was measured. The average distance measured three times on each transect lines, two lines per belt, was deemed the unit of visibility (unit: m). Then, the spotlight method was used to calibrate visibility. A spotlight (Sure Fire 6P, 65 lm) was directed into the tree belt. An individual carrying a light meter (INS DX-200), followed the light and walked into the tree belt until the meter presented a value that was similar to the background reading. Then the distance between the receiver and spotlight was measured. The mean distance measured six times on the two transect lines was termed the unit of visibility (unit: m). The precision of the spotlight method was to 0.1 m. These two methods were compared and the experimental results revealed that the difference between the two methods was approximately 0.5 m. This test showed that the visibility method is reliable. However, the two methods failed to measured the visibility of *Ficus microcarpa* L.f. 6, *Podocarpus macrophyllus* 2 and *Palaquium formosanum* Hayata 2 tree belts because the visibility distance exceeded the width of these tree belts. Therefore, the visibilities of these three tree belts were determined by our experience.

2.6. Definitions

dB A: The human ear is more sensitive at medium frequencies. Thus, in order to take into consideration the human perception, low and high frequency are reduced by the A-weighting filter. The resulting sound level is designated A-weight, and its unit is dB A (Wilson, 1994).

Relative attenuation: Data measured over open ground represents the effect of distance alone, whereas data from the tree belt include effects of the distance and the vegetation. Consequently, the difference between the two values produces the relative attenuation of every measuring site within the tree belt.

Excess attenuation: Mean value of relative attenuation per 20 m (dB A/20 m).

2.7. Statistics and mapping

Stepwise multiple regression was employed to evaluate the importance of the noise reduction factors of 35 tree belts. In this model, the dependent factor was the relative attenuation, and the independent factors were visibility, width, height and length of the tree belts. First, curve-fitting was used to determine the correlation between dependent and independent factors, respectively. According to the curve-fitting result, the independent factors were transformed to an appropriate (logarithmic) form and then a multiple regression model was determined.

In order to examine further the more significant factors (visibility and width), the less effective factors (height and length) in the multiple regression model should be fixed in advance, so that they could be excluded temporarily. The observations show that the influence of height becomes insignificant when it exceeds 4 m. Also, the effect of length becomes stable when the length exceeds 50 m. For this reason, the tree belts chosen from the 35 tree belts were ≥4 m high and ≥50 m long. As result, 18 tree belts (with symbol ◎ in Table 1) were chosen for further examination. Eventually, a map of visibility and width for noise reduction was constructed by projecting the relative attenuation of the 18 tree belts on the visibility/width grid.

3. Results

3.1. Excess attenuation of all tree belts

The excess attenuation of the 35 tree belts is illustrated in Fig. 5. Three groups are apparent.

- *Group 1*: Effective reduction region. Excess attenuation exceeded 6 dB A. All tree belts were comprised of large shrubs with a visibility of less than 5 m.
- *Group 2*: Sub-reduction region. Excess attenuation was 3–5.9 dB A. This group included trees and shrubs whose visibility ranged between 6 and 19 m.
- *Group 3*: Invalid reduction region. Excess attenuation was less than 2.9 dB A. This group included sparsely distributed tree and shrubs, whose visibility exceeded 20 m.

3.2. Multiple regression model

The β-value in the multiple regression model (Table 2) shows that the visibility within a tree belt had a negative logarithmic correlation with relative attenuation, while height, width and length had a positive logarithmic correlation. The order of significance of the tested factors is: visibility, width, height and length of tree belt.

3.3. Noise reduction effect

Relative attenuation was projected on a grid of visibility/width using the data of 18 tree belts (Fig. 6). The results revealed that relative attenuation decreased with visibility and increased with width of the tree

Table 2
The multiple regression model of 35 tree belts

Variable	Unstandardized coefficient (B)	Standardized coefficient (β)	t-Value
Visibility (log)	−3.77	−0.77	−21.6***
Depth (log)	3.04	0.41	16.6***
Height (log)	0.83	0.09	3.9*
Width (log)	1.02	0.10	3.2*
Constant	2.75		2.1*

$R^2 = 0.76$; $F = 170.2$.
* $P \leq 0.05$.
*** $P \leq 0.001$.

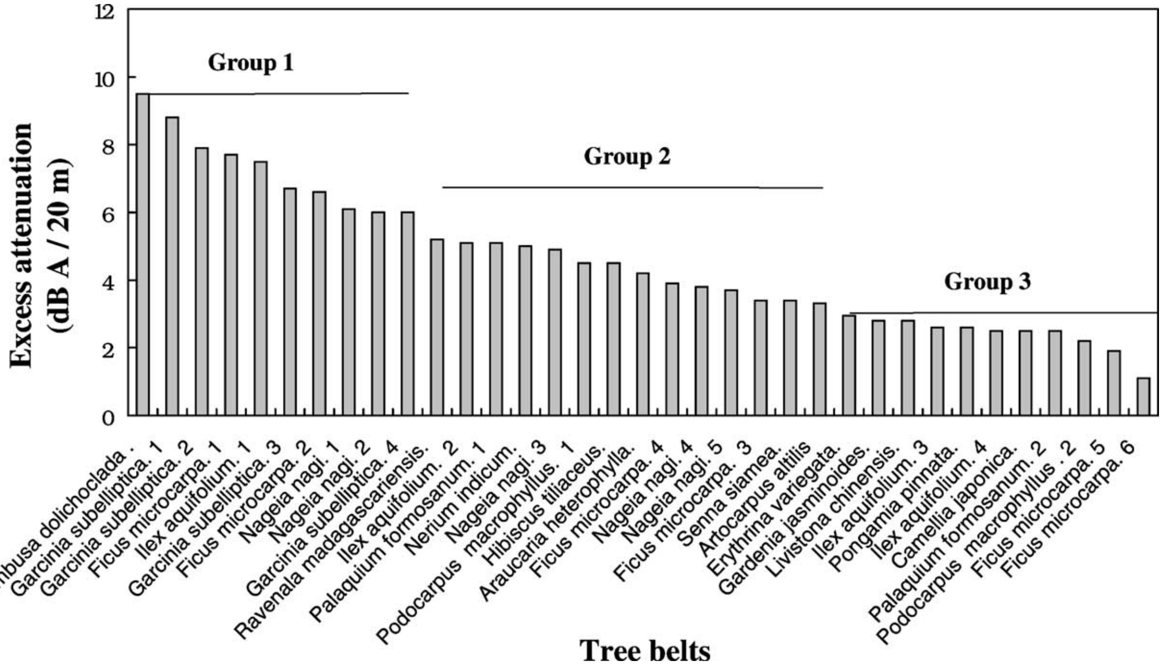


Fig. 5. The excess attenuation of 35 tree belts.

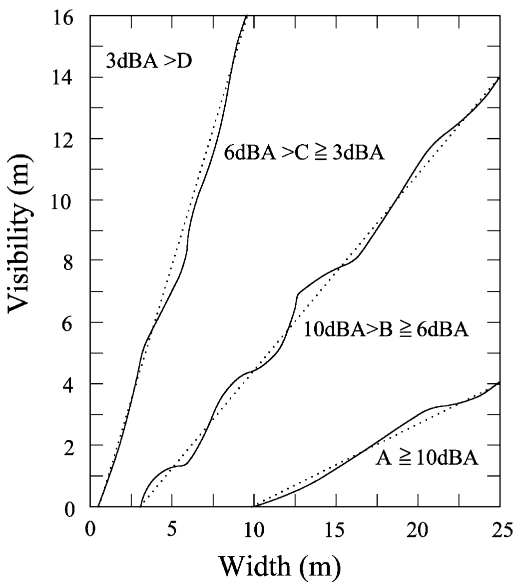


Fig. 6. Visibility and width in relation to relative attenuation.

belts. The solid lines indicate the relative attenuation and the dotted line indicates the fitting curve of solid lines. The lines 10, 6 and 3 dB A divided the entire area into four regions (A–D).

Region A was most effective in reducing noise in that the relative attenuation exceeded 10 dB A. The 10 dB A slope was 0.26 which revealed that visibility was an influential factor. Region B was the second most effective in noise reduction with relative attenuation of 10–6 dB A. The 6 dB A slope was 0.65 which indicated that width was a more vital factor. Region C was less effective in noise reduction with a relative attenuation of 6–3 dB A. The 3 dB A slope was 1.6, which indicated that width was the sharpest factor. Finally, region D was the least effective which had a relative attenuation less than 3 dB A.

4. Discussion

Sound reduction occurs via normal attenuation and excess attenuation (Herrington, 1976; Harris, 1979). Normal attenuation is due to spherical divergence

(Wilson, 1994) and friction between atmospheric molecules when sound progresses (Herrington, 1976). This has been termed the distance effect; noise attenuation increases with distance. Furthermore, reflection, refraction, scattering and absorption effects due to any obstruction between a noise source and a receiver results in excess attenuation (Herrington, 1976; Harris, 1979). The barrier effect is an example of the latter and is measured via relative attenuation.

In the 35 tree belts studied, Group 1, that consisted of dense shrubs, had the best reduction effect (Fig. 5). Previously, low hedges were considered useless for noise reduction (Ishii, 1994), but this was where the top of the hedge was lower 0.5–1 m than the receiver. Herrington (1976) concluded that hedges acting as windbreaks can produce considerable noise attenuation. The tree belts in Group 1 had dense foliage and branches which reduced noise at level of the receiver. Thus, dense shrubs which are higher than the receiver provide the greatest noise reduction. Group 2 had the second-best noise reduction effect. In this group, trees differed dramatically, but dense foliage and branches still resisted acoustic waves. It seems that shrubs and trees with low forking have a greater effect on noise reduction. Group 3 had very little effect on noise. Since any forking and branching was high up, there were few obstructions to absorb noise.

Density, height, length and width of tree belts are the most effective factors in reducing noise rather than leaf size and branching characteristics (Cook and Haverbeke, 1974). Density, height, length and width diffuse noise (Cook and Haverbeke, 1974) and the leaf size and branching characteristics have resonant absorption (Aylor, 1972). Diffusion prevailed over absorption to reduce the acoustic energy (Cook and Haverbeke, 1974). Therefore, the construction and form of the tree belt were the most obvious factors in noise reduction (Cook and Haverbeke, 1974).

The lower the visibility, the higher the density, and the more foliage and branches to reduce sound energy, the greater the scattering effect (Aylor, 1972; Cook and Haverbeke, 1974). In this study, visibility was the prominent noise reduction parameter, having a logarithmic negative relationship with relative attenuation. Eyring (1946) measured noise reduction in tropical rain forest and his results show a relationship similar

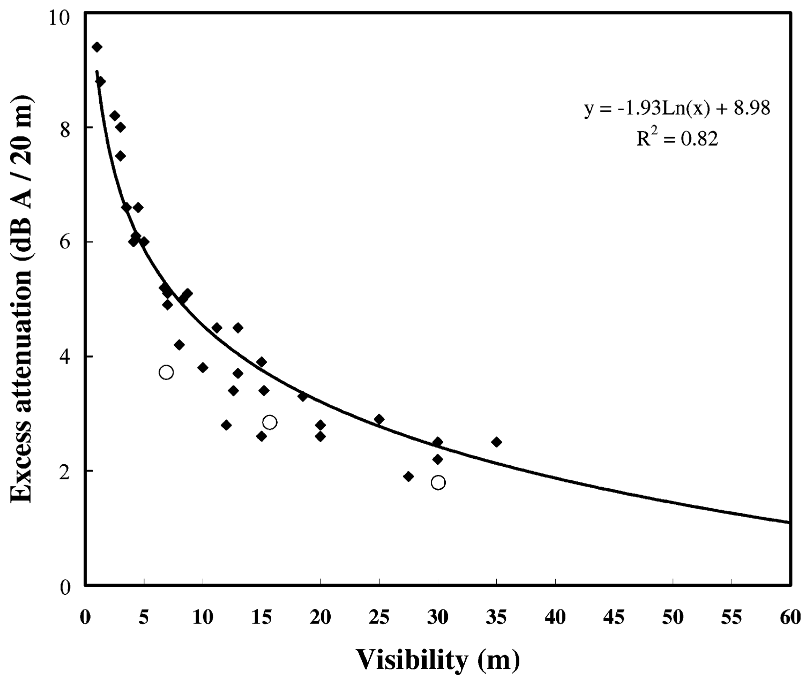


Fig. 7. Regression of visibility and excess attenuation. The symbol (◆) indicates data taken from this study; the symbol (○) represents the data adapted from Eyring's (1946) study at a Panama jungle.

to this study (Fig. 7), although the slope of that relationship was more gradual than this study. Eyring's study was conducted over visibilities of 6–30 m and not under 6 m and our results show a steep slope less than 5 m (Fig. 7)

Width of vegetation belts is the other significant noise reduction factor. Greater width resulted in more trees on the acoustic pathway, producing greater absorption and diffusion (Cook and Haverbeke, 1974). As well, structure and foliage of vegetation can disperse the concentrating acoustic wave at locations near the noise source (Cook and Haverbeke, 1974) and scattering decreased as the distance from the sound source increased (Embleton, 1963). This confirmed that width had positive relations with relative attenuation. Other studies have also concluded that tree belt width of at least 30 m provides greater reduction in noise (Reethof, 1973; Cook and Haverbeke, 1974).

A higher tree belt provides a greater surface, and therefore more opportunities for diffusion and absorption (Cook and Haverbeke, 1974) and this was shown by our study.

When the tree belt was longer, acoustic wave disturbance produced diffraction phenomena that were higher and the noise reduction effects were greater. Reethof and Heisler (1976) have indicated that vegetation belts should be more than 60 m long to provide the greatest reduction.

In all of the vegetation belts examined, shrubs were the most effective in reducing noise owing to scattering from their dense foliage and branches, while tree belts of sufficient height were superior due to their diffusion and absorption of noise. However, most shrubs were low, while trees had little foliage and fewer branches at ear height. Therefore, both shrubs and trees must be taken advantage of. That is, shrubs should be planted under trees, to enable the tree belts to provide the best reduction effect.

This study summarized experimental data in single map (Fig. 6), incorporating the relationships between relative attenuation and both visibility and width. This study provides data of use to environment designers. For example, designers can reduce noise by 6 dB A via suitable plantings. As well, belts of tree and shrubs could be planted based on a 1 m visibility and 5 m width, or 10 m visibility and 18 m width. Moreover, the visibility/width slope changed regularly (Fig. 6). This implies that visibility was the greatest factor on the region A condition (slope of visibility/width was less than 0.26). Consequently, altering the visibility was effective. However, width was more important in B–D conditions (slope exceeded 0.65). This indicated that transforming width was also effective.

Beranke and Vèr (1992) have pointed out that the noise attenuation of a point source is better than that of a line source by a barrier and however the attenuation trends between line source and point source are similar. Even though the point source was used in this study, it infers that the noise reduction effect of line source and point source by tree belts are similar. Nevertheless, further investigation on the line source attenuation by tree belts will be needed and the results should play an important role on the reduction of traffic noise. This study also examined the total attenuation by tree belts. The relationship of tree belts and attenuation mechanism has been realized. Nevertheless, the relationship of tree belts and frequency attenuation should be further examined in future.

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