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Mixed Coniferous Broad-Leaved Forests as Road Shelter Forests: Increased Urban Traffic Noise Reduction Effects and Economic Benefits

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Abstract: Establishing road shelter forests is a key method to reduce traffic noise pollution. However, the characteristics of various types of road shelter forests and their effectiveness in reducing traffic noise remain extensively unexplored. This study focused on five types of pure road shelter forests (PFs) and one type of mixed coniferous broad-leaved forest (MCBLF). By conducting field noise monitoring and spectrum simulations, we analyzed average mass density, additional noise reduction and economic benefits. With a forest belt width of 60 m, the MCBLF reduced additional noise by 6.6 dB(A). Additionally, Forest height, crown shape, average mass density and noise frequency were all positively linked to noise reduction. The width of shelter forests was the main factor affecting noise reduction. Linear regression analysis results showed that cumulative mass surface density was a significant factor in noise reduction ($p < 0.01$, $R^2 = 0.93$). Furthermore, the type and composition of the shelter forest had indirect effects on noise reduction. The MCBLF had better noise-reducing effects compared to both broad-leaved PFs and needle-leaved PFs due to its more complex structure. Interestingly, as the forest belt became wider, the noise reduction benefits per unit area decreased, implying that a 10 m wide forest belt offered higher economic returns. Considering that a 10 m wide shelter forest belt did not meet noise reduction requirements. This study suggested that the 20 m wide MCBLF was an optimal choice as an urban road shelter forest, providing both effective noise reduction and maximized economic benefits. Our findings provide a basis for the construction and sustainable development of road shelter forests with noise reduction functions.

Keywords: road shelter forests; shelter forest characteristics; traffic noise; average mass surface density; additional noise reduction

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1. Introduction

With fast economic growth and the expansion of urban scales and traffic networks, road traffic noise has become a global environmental pollution risk [1]. According to statistics, there are now 1.47 billion automobiles globally [2]. In 2023, the world's population reached 8 billion people [3]. This means that, on average, there is one car for every five people in the world. Notably, the number of automobiles will keep growing, so road traffic noise pollution will probably continue to worsen. Road traffic noise not only affects the ecological environment [4,5] and economic development [6,7], but it also harms people's health and well-being [8,9]. Therefore, using effective noise reduction methods to reduce noise is very important for sustainable social development.

There are two main methods to reduce traffic noise. A method is to build sound barriers, and another method is to establish road shelter forests. Sound barriers can reduce traffic noise effectively, but they are expensive and often feature monotonous designs [10]. Establishing road shelter forests is a green method to reduce traffic noise, and offers significant advantages, such as low cost and ease of maintenance [11]. Shelter forests reduce noise by absorbing, reflecting, and obstructing sound. Compared with traditional noise barriers, shelter forests are superior in enhancing landscapes, alleviating the heat island effect and promoting biodiversity [12,13], which makes shelter forests an indispensable ecological landscape in road planning. Additionally, they also bring other benefits, like improving the environment, helping the economy development, and creating social value. Previous studies have further quantified the economic benefits of shelter forests. They use methods to calculate the value, such as the market method, replacement cost method, and simulated market method [14]. These methods provide a basis for quantitatively assessing the economic contributions of shelter forests. However, the ecological benefits of shelter forests are multifaceted, including oxygen release, carbon sequestration, dust retention, and noise reduction [15]. These ecosystem services span multiple disciplines and have irreplaceable value. Thus, it is important to use a comprehensive ecosystem assessment, centered on ecosystem protection [16,17]. Finally, suitable policy instruments can also help measure the multiple ecological services provided by shelter forests [18].

Previous studies primarily focused on the noise reduction mechanisms of individual characteristics of road shelter forests. For example, research indicated that features such as the leaves, trunks, and bark of larch trees (*Larix gmelinii* (Rupr.) Kuzen) in Salzburg, Austria, were closely related to noise reduction effects [19]. Leaves can reduce noise through vibration and reflection [20]. Trunks reduce noise by scattering sound waves [21]. Additionally, the cavity resonance of leaves and bark can absorb some noise [22]. Furthermore, rough bark and dense leaves were effective at absorbing and reducing noise [23]. Further research found that sound waves can pass through gaps between trees [24]. A study from China found that an increase in forest coverage, coupled with the enhanced ability of leaves to scatter sound energy, correspondingly improved noise reduction [25]. In Turkey, researchers studying the E-80 highway found that pure shelter forests (PFs) of *Populus nigra* reduced noise better than PFs of *Pinus sylvestris* L. [26]. In Beijing, studies showed that the annual noise reduction effects of needle-leaved PFs were better than those of broad-leaved PFs, and the annual noise reduction effects of mixed forests were the worst [27]. Therefore, we concluded that noise reduction depends on the structural characteristics of trees (such as leaves, trunks, and bark) and species selection, as well as factors like forest coverage, forest belt width, season, time, and topography [28]. A study in Shenzhen, China, found that more forest coverage and higher leaf areas made noise reduction better [29]. Research in Switzerland showed that increasing forest coverage from 5% to 95% near residential areas reduced road traffic noise by 6 dB(A) [30]. Similar results were seen in other areas. In Thessaloniki, *Pinus brutia* located 60 m from the road effectively reduced noise levels by 6 dB(A) [31]. Even small forest belts as narrow as 9.1 m reduced noise by 2 to 3 dB(A) [32]. Therefore, Attenborough noted that narrow shelter forests had considerable potential for reducing traffic noise [20]. Furthermore, both season and time of day also significantly influence the noise reduction performance of shelter forests. Research in southern Ontario, Canada, showed that forests reduce more noise in summer than in winter [33]. In Belgrade, Serbia, mixed broad-leaved forests reduced noise more during the middle of the day than in the morning or evening [34]. Finally, topography has also been proven to be also an important factor affecting noise levels. Research by Hosseini S.A.O. et al. found that noise reduction effects decreased as the longitudinal gradient of the road increased [35].

Although existing studies have explored the noise reduction mechanisms of shelter forests, including the effects of basic characteristics, species selection, forest coverage, forest belt width, season, time, and topography on noise reduction, there are still research gaps. For example, comparative studies on the noise reduction effects of different tree species under the same conditions are relatively rare, (especially research involving more than three species). Additionally, the noise reduction effects of different tree species under different width conditions have not been systematically studied. Based on previous studies, we thought that PFs would be better at reducing noise than mixed coniferous broad-leaved forests (MCBLFs). We also believed that narrower shelter forests would have better noise reduction benefits. We expected that evergreen broad-leaved PFs, like *Ilex chinensis* Sims, would reduce noise better than evergreen needle-leaved PFs, such as *Cedrus deodara* (Roxb.) G. Don.

To test this hypothesis, we selected five types of PFs (*C. deodara* (Roxb.) G. Don., *Prunus serrulate* Lindl., *Zelkova serrata* (Thunb.) Makino, *I. chinensis* Sims and *Prunus cerasifera* Ehrhar f.) and one type of MCBLF. The PFs consist of single tree species and the MCBLF consists of eight tree species. We analyzed the basic characteristics of these forests, as well as their mass density, noise reduction ability, and economic benefits. This study aimed to (1) analyze the structural characteristics of different road shelter forests and their impact on noise reduction, (2) compare the noise reduction effects of various noise frequencies across different forest belt widths, and (3) assess the economic benefits of noise reduction functions of different types of road shelter forests. This study will provide a scientific basis for the establishment of road shelter forests and the assessment of their noise reduction effects.

2. Materials and Methods

2.1. Study Area Overview

The study area was located on the southern side of the eastern section of National Highway 312 in Qixia District, Nanjing, Jiangsu Province, China (32°07′26′′~32°07′34′′ N, 118°54′34′′~119°14′56′′ E) [36] and the eastern side of the Third Ring Road in Qixia District, Nanjing, Jiangsu Province, China [37] (32°07′39′′~32°07′43′′ N, 119°00′10′′~119°00′10′′ E) (Figure 1). The study region belongs to the North subtropical humid climate zone. The average annual temperature is 15.3 °C, with an average relative humidity of 76%. Annual precipitation is approximately 1000 mm, occurring over roughly 110 days yr^{-1}. The MCBLF along National Highway 312 consists of 8 tree species: *C. deodara* (Roxb.) G. Don., *Populus euramericana* L., *Lagerstroemia indica* L., *Cinnamomum camphora* (L.) Prest, *Ulmus pumila* L., *Z. serrata* (Thunb.) Makino, *I. chinensis* Sims, and *P. cerasifera* Ehrhar f. The five PFs along the Third Ring Road consist of *P. cerasifera* Ehrhar f., *I. chinensis* Sims, *P. serrulata* Lindl., *Z. serrata* (Thunb.) Makino, and *C. deodara* (Roxb.) G. Don. This study focuses on road shelter forests, with the following conditions for selecting experimental plots: (1) the road shelter forest width must be ≥30 m, and the forest must be uniform; (2) the background noise level must be 45 ± 2 dB(A) in the absence of traffic. In addition, the ground conditions of all the selected plots are similar (all have level terrain and are covered with leaves), ensuring negligible impact on the noise measurement results.

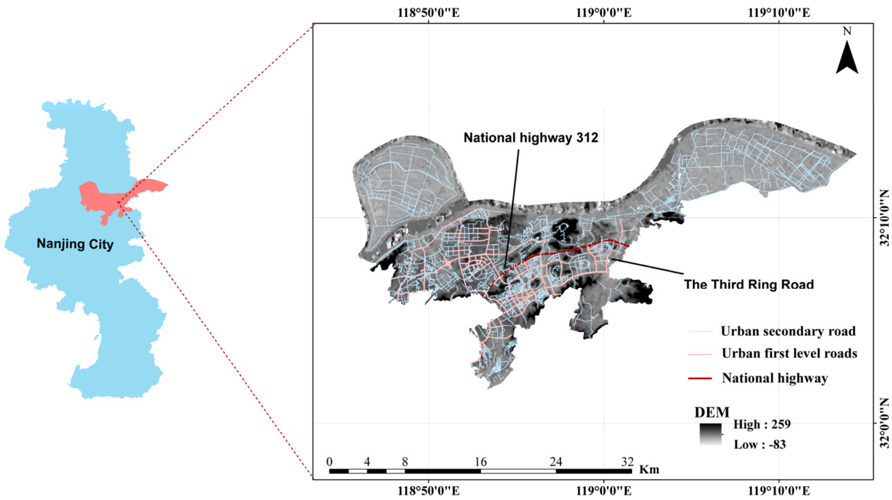


Figure 1. Geographic location of the study area. The left side is the geographic location of Qixia district in Nanjing City. The right side indicates the locations of the MCBLF along National Highway 312 and the PFs along the Third Ring Road.

2.2. Average Crown Mass of Road Shelter Forests

Estimation of the crown volume is based on crown shape and relevant characteristic parameters. For each type of shelter forest, 3 to 5 samples (20 cm × 20 cm × 20 cm) were selected during the non-flowering and non-fruiting periods, with each sample having a leaf volume of 8000 cm^3. These samples were sealed in plastic bags and brought back to the laboratory for mass measurement. The average mass of the sample, M_0 (kg), was used to further estimate the average mass of the crown. The formula used for this calculation is as follows:

$$M_{Crown} = \frac{V_{Crown} \times M_0}{8} \times 10^3 \quad (1)$$

In this formula, M_{Crown} refers to the average mass of the crown (kg); V_{Crown} refers to the volume of the crown (m^3); and M_0 is the average mass of the sample (kg).

Given the irregular shape of forest crowns, for ease of measurement and calculation, it was assumed that the crown surrounding the trunk was symmetrical [22]. The crown was approximated as a regular geometric shape. A height indicator was used to measure tree height (m), height under branch (m), and crown height, h (m). We used the projection method to measure the forest crown diameter, D (m). The corresponding formulas for estimating crown volume are provided in Table 1.

Table 1. Study area's approximate forest crown shape and volume calculation formula.

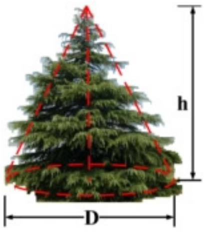
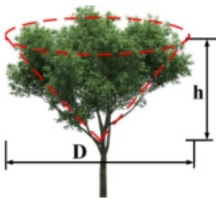
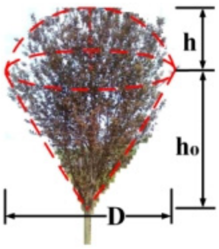
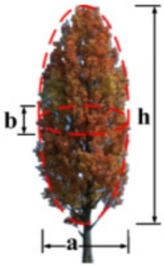
Rank	Crown Shapes	Regular Shapes	Crown Volume	Shelter Forests
1		conical crown	$V = \frac{\pi}{12} D^2 h$	*Cedrus deodara* (Roxb.) G. Don.
2		inverted conical crown	$V = \frac{\pi}{12} D^2 h$	The Third Ring Road: *Prunus serrulate* Lindl.; G312: MCBLF
3		spherical conical crown	$V = \frac{\pi h_0}{12} D^2 + \frac{\pi h}{6} \left(\frac{3}{4} D^2 + h^2 \right)$ (h is the height of the crown ball; h_0 is the height of the spherical conical crown)	The Third Ring Road: *Zelkova serrata* (Thunb.) Makino *Prunus cerasifera* Ehrhar f.
4		near-spherical crown	$V = \frac{\pi}{6} D^3$	The Third Ring Road: *Ilex chinensis* Sims

Table 1. *Cont.*

Rank	Crown Shapes	Regular Shapes	Crown Volume	Shelter Forests
5		ovoid crown	$V = \frac{1}{6}\pi abh$ (a or b is the largest crown width in east–west and north–south directions)	G312: MCBLF

2.3. Average Surface Density of Road Shelter Forests

The weight of a single tree is 100%, with the trunk accounting for 64.11% and the roots, branches, and leaves together accounting for 35.89% [38]. If the mass of the roots and part of the trunk is removed, it can approximately be considered that the crown mass accounts for 30% of the total tree mass. Therefore, we can calculate the total mass of a single tree based on the proportion of the crown mass (Formula (2)). The total mass of the shelter forests (Formula (4)) was calculated by multiplying the mass of a single tree by the total number of trees (Formula (3)) within the measured area of the shelter forests. This total mass was then divided by the volume of the shelter forest spaces to calculate the average mass density of the shelter forests (Formula (5)). Finally, the average mass density was multiplied by the width of the shelter forest to obtain the average surface mass density of the shelter forests (Formula (6)).

$$M_{single} = \frac{M_{Crown}}{30\%} = \frac{V_{Crown}M_0}{24} \times 10^4 \quad (2)$$

$$j = \frac{L}{d} \times n \quad (3)$$

$$M_{total} = j \times M_{single} = \frac{L}{d} \times n \times M_{single} \quad (4)$$

$$\overline{\rho} = \frac{M_{total}}{L \times H \times D} = \frac{10^4}{24} \times \frac{nV_{Crown} \times M_0}{d \times H \times D} \quad (5)$$

$$\overline{m} = \overline{\rho} D_i = \frac{10^4}{24} \times \frac{nV_{Crown} \times M_0}{d \times H \times D} \times D_i \quad (6)$$

D represents the width of the shelter forests (m); L is the length of the shelter forest (m); H is the average tree height (m); j is the total number of trees; d is the spacing between trees (m); n is the row numbers of the shelter forests; D_i is the width of the shelter forests at the i-th measurement point (m); $\overline{m}$ is the average mass surface density of the shelter forests (kg m^{-2}); and $\overline{\rho}$ is the average mass density of the shelter forests (kg m^{-3}).

2.3.1. Calculation of Average Mass Surface Density for PFs

The density distribution within shelter forests was often uneven, with varying masses of branches and leaves (or stems) within different volumes. The term 'Average Mass Density' refers to the mass of branches and leaves (or stems) per unit volume, while 'Average Mass Surface Density' refers to the average mass of branches and leaves (or stems) per unit area.

$$\overline{m} = \overline{\rho}\, d \quad (7)$$

In the formula, $\overline{m}$ is the average mass surface density of the shelter forests (kg m^{-2}); $\overline{\rho}$ is the average mass density of the shelter forests (kg m^{-3}).

2.3.2. Calculation of Average Mass Surface Density for the MCBLF

The average mass surface density of the MCBLF is the sum of the average mass surface densities of its sub-forest belts. Suppose the total mass of the MCBLF and its sub-forest belts are $M,\ M_1,\ M_2, \ldots, M_i, \ldots, M_n$; the average mass surface densities are $\overline{m},\ \overline{m_1},\ \overline{m_2},\ \ldots, \overline{m_i}, \ldots, \overline{m_n}$; average mass densities are denoted as $\overline{\rho}$, $\overline{\rho_1}$, $\overline{\rho_2}$, …, $\overline{\rho_i}$, …, $\overline{\rho_n}$; the shelter forest widths are $d,\ d_1,\ d_2, \ldots, d_i, \ldots, d_n$; and the cross-sectional areas are $S,\ S_1,\ S_2, \ldots, S_i, \ldots, S_n$. The relationship among these parameters can be expressed as follows:

$$
\begin{aligned}
M &= \sum_{i=1}^{n} M_i = M_1 + M_2 + \ldots + M_i + \ldots + M_n \\
&= \overline{\rho_1} S_1 d_1 + \overline{\rho_2} S_2 d_2 + \ldots + \overline{\rho_i} S_i d_i + \ldots + \overline{\rho_\mathrm{n}} S_\mathrm{n} d_\mathrm{n} \\
&= \overline{m_1} S + \overline{m_2} S + \ldots + \overline{m_i} S + \ldots + \overline{m_n} S \\
& S = S_1 = S_2 = \ldots = S_i = \ldots = S_n \\
& \overline{m} = \frac{M}{S} = \overline{m_1} + \overline{m_2} + \ldots + \overline{m_i} + \ldots + \overline{m_n} = \sum_{i=1}^{n} \overline{m_i}
\end{aligned}
\tag{8}
$$

$\overline{m}$ represents the average mass surface density of the MCBLF (kg m^{-2}); $\overline{m_i}$ is the average mass surface density of the i-th sub-forest belts (kg m^{-2}); $\overline{\rho_i}$ is the average mass density of the i-th sub-forest belts (kg m^{-3}); and n is the width of the i-th sub-forest belts (m). (When n = 1, the shelter forest is a PF).

2.4. Noise Reduction and Additional Noise Reduction in Road Shelter Forest

Observations were conducted during the daytime from 8:30 am to 12:00 am and from 1:00 am to 5:00 am in May. We used a portable noise spectrum analyzer (HS6288B, Shanghai Shourong Industrial Equipment Co., Ltd., Shanghai, China) to measure the noise spectrum. Before each measurement, an acoustic calibrator (BK4231, B&K, Nærum, Denmark) was used to calibrate the HS6288B analyzer. Measurements were taken under clear weather conditions with a relative humidity of around 50% and wind speeds below 5 m s^{-1}. During the observation, it was ensured that the road had continuous vehicles, and the real-time road traffic noise level was at least 10 dB(A) higher than the background noise (45 $\pm$ 2 dB(A)) to neglect the influence of environmental noise on the observed data.

The first HS6288B analyzer was consistently placed at the front edge of the shelter forests at a height of 1.2 m above the ground [39]. Other HS6288B analyzers were placed within the shelter forests at widths of 10 m, 20 m, 30 m, 40 m, 50 m, and 60 m, all at the same height (Figures 2 and 3). According to ‘Environmental Noise Monitoring’ outlined in the Chinese Standard for ambient noise (GB 3096-2008), field tests were conducted [40]. Real-time traffic noise was used as the test noise source, and noise levels and frequency characteristics were observed at 10 m, 20 m, 30 m, 40 m, 50 m, and 60 m within 6 shelter forests. The sampling interval times of the HS6288B were set to 0.1 s, with a fast (F) time. Each measurement point was continuously measured for 5 min. In addition, we used the spectrum analysis function of HS6288B to observe the noise frequency characteristics. The measured data included the equivalent continuous sound pressure level Leq (A) at each center frequency of octave bands (31.5 Hz, 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, 8000 Hz), with each frequency point measured for 1 min.

Valid test data were used to calculate noise reduction (R_{noise}) and additional noise reduction (ΔL); R_{noise} is defined as the difference in sound pressure levels measured at points before and after the shelter forests, also known as the total noise reduction. The expression is as follows:

$$R_{noise} = 20lg\left(\frac{P_i}{P_t}\right) = L_i - L_t \tag{9}$$

where R_{noise} is the total noise reduction in the shelter forests (dB(A)); P_i and L_i are the sound pressure (Pa) and sound pressure level (dB(A)) on the incident wave side; and P_t and L_t are the sound pressure and sound pressure levels on the transmitted wave side.

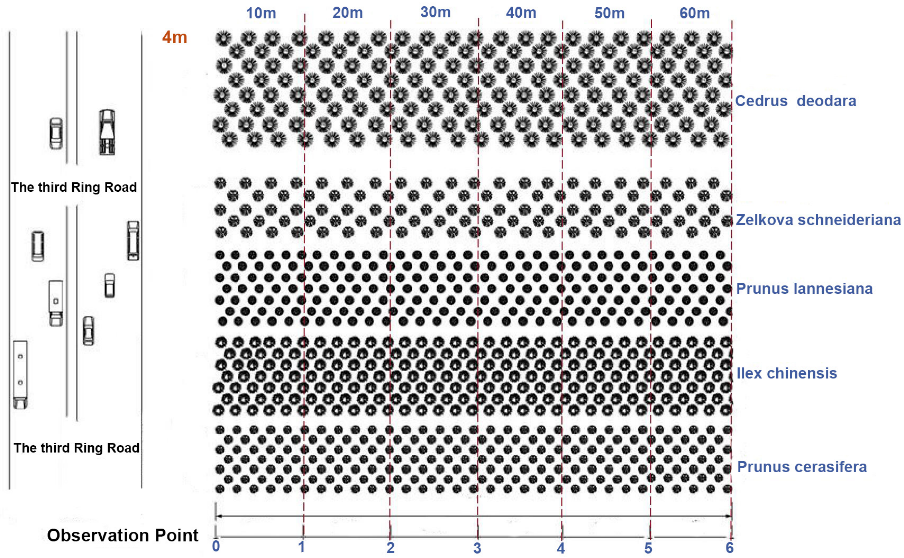


Figure 2. Observation points of road PFs on the southeast side of the Third Ring Road.

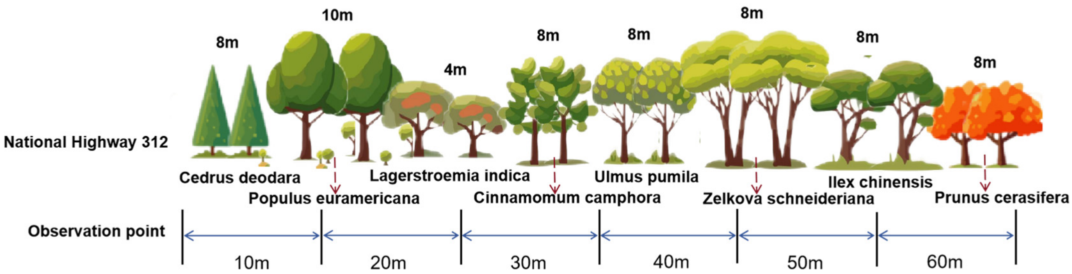


Figure 3. Observation points of the road MCBLF on the southeast side of National Highway 312.

The additional noise reduction (ΔL) is the difference between the sound pressure level measured in the shelter forest and the sound pressure level of the blank control (not in the shelter forest). The ΔL represents the noise reduction in the shelter forest. The expression is as follows:

$$\Delta L = R_t - R_0 \tag{10}$$

In this formula, ΔL is the additional noise reduction in the shelter forests (dB(A)); R_0 and R_t are the noise reduction at a specific point with the shelter forests and without the shelter forests. (Table S3) (It was hypothesized that the sound pressure level of the noise source L_i during both measurements is equal or similar).

2.5. Economic Benefits of Shelter Forest Noise Reduction

To accurately assess the economic value of shelter forests on noise reduction, the equivalent substitution method was used in this research. This method estimated the economic value of the noise reduction provided by shelter forests by comparing it with the construction cost of an equivalent noise-reducing structure (e.g., the construction of noise barriers along the roadside). Based on the Forest System Service Function Evaluation Specifications [41], the calculation formula was as follows:

$$V_{noise\ reduction} = R_{noise} \times P_{noise} \tag{11}$$

$V_{noise\ reduction}$ represents the value of road shelter forests on noise reduction (RMB yr^{-1}); R_{noise} is the total noise reduction in road shelter forests (dB(A) yr^{-1}); and P_{noise} is the cost of noise reduction (RMB dB(A) $^{-1}$). In this study, the P_{noise} was selected from existing research, and the noise reduction cost was 7.66 RMB dB(A) $^{-1}$ [42]. The noise reduction value per unit area was calculated by dividing the $V_{noise\ reduction}$ by the area of the shelter forests (hm^2) (Table S3).

To ensure the comparability of economic benefits, this article assumed that the length of all types of shelter forests was the same (1.0×10^6 m) to calculate the noise reduction value per unit area (RMB hm^{-2} yr^{-1}).

2.6. Model Application

To establish the relationship between the noise reduction value of shelter forests and their mean cumulative surface density, we used noise reduction value as the dependent variable (y) and mean cumulative surface density as the independent variable (x). We chose a log-log nonlinear regression model because it provided the best fit and had good statistical significance. The model was written as ln(Y) = βnln(Xn) + u. This model assumed that the relationship between the log-transformed data was linear and that the residuals (u) followed a normal distribution. We checked these assumptions by analyzing the residuals. The model fit the data well, with an R-squared value of 0.9297 and $p < 0.01$, which showed a strong correlation. To further assess the economic benefits of different shelter forest types, we used a Monte Carlo simulation. In this simulation, we assumed that all the data followed a triangular distribution [43]. We randomly sampled 10,000 data points and created a probability distribution curve. Nonlinear curve fitting was then applied, and the R-squared values exceeded 0.99, showing a very good fit as well.

2.7. Statistical Analysis

Data were organized using Microsoft Excel 2021 (Microsoft, Redmond, WA, USA) [44]. Statistical analyses were used by IBM SPSS Statistics v.17.0 (IBM Corp., Armonk, NY, USA) [45]. Nonlinear regression analysis in R 4.4.1 (Miseq, MA, USA) was employed to test whether the factors had a statistically significant impact on the observed variables. The map of Figure 1 was made by ArcGis 10.8.1 (The map approval number is GS262 (2019)1822). Flow diagram of sequential study steps and data sources (Figure 4).

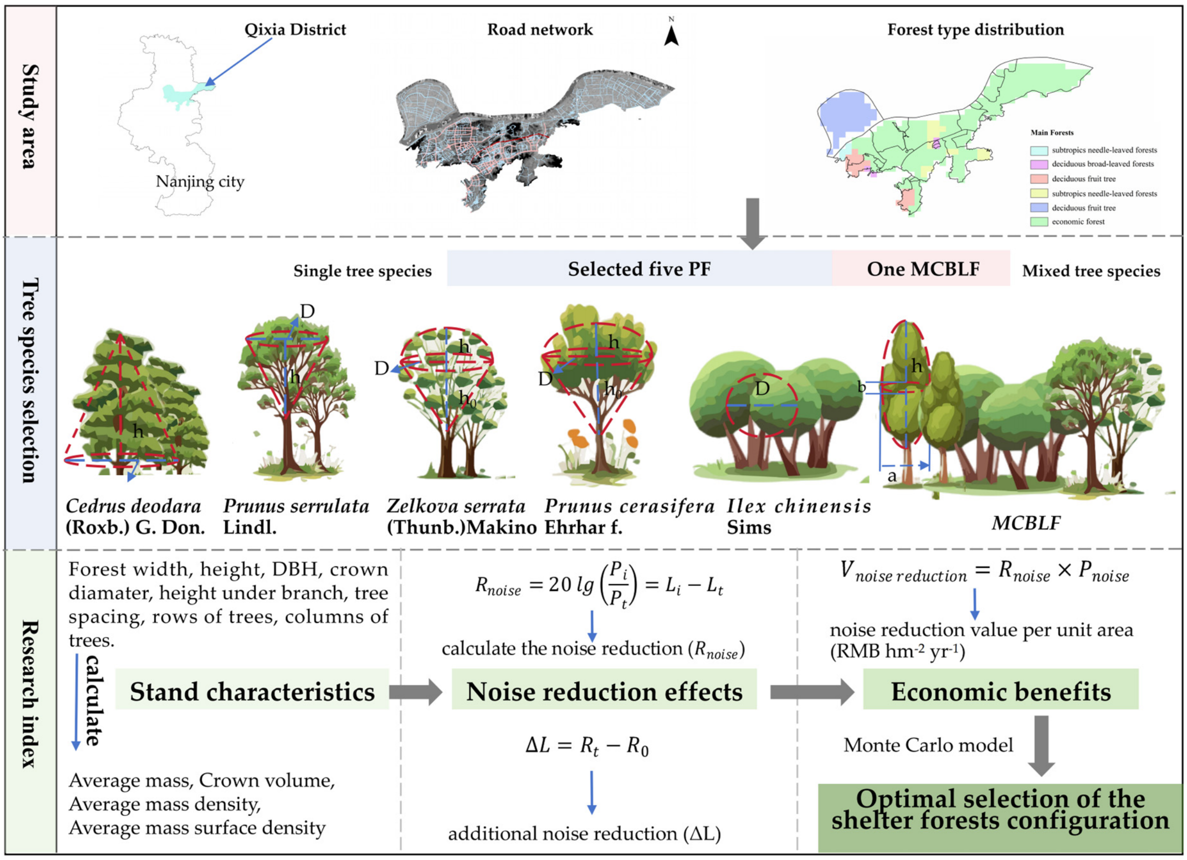


Figure 4. Flow diagram of sequential study steps and data sources.

3. Results

3.1. Stand Characteristics of Shelter Forest Belts

Table 2 and Table S1 showed that *C. deodara* (Roxb.) G. Don. was a typical evergreen needle-leaved forest with a conical crown. The average height of *C. deodara* (Roxb.) G. Don. was 6.4 m, and its DBH was 6.6 cm. *P. serrulate* Lindl., a deciduous broad-leaved forest, had the lowest average height among the six shelter forest types at just 3.2 m. Because of its inverted conical crown, it was particularly effective at reducing noise from lower sources. *P. cerasifera* Ehrhar f., a deciduous broad-leaved forest, had a spherical conical crown and a relatively low average height (4.5 m). *Z. serrata* (Thunb.) Makino had the largest crown diameter (4.5 m) and also had a spherical conical crown. *I. chinensis* Sims, an evergreen broad-leaved forest, featured a near-spherical crown and a larger DBH (8.5 cm). The MCBLF was composed of needle-leaved forests and broad-leaved forests, which were characterized by mixed crown shapes. The average height of the MCBLF was 12.5 m and its DBH was 11.4 cm. Due to its unique arrangement, the rows of trees could not be confirmed.

Table 2. Basic characteristics of road shelter forests.

Basic Characteristics	*C. deodara* (Roxb.) G. Don.	*P. serrulate* Lindl.	*Z. serrata* (Thunb.) Makino	*I. chinensis* Sims	*P. cerasifera* Ehrhar f.	MCBLF
Forest belt structure	PF	PF	PF	PF	PF	MCBLF
Forest form	evergreen needle-leaved	deciduous broad-leaved	deciduous broad-leaved	evergreen broad-leaved	deciduous broad-leaved	mixed of needle-broad
Crown shape	conical	inverted conical	spherical conical	near spherical	spherical conical	mixed shape
Forest width (m)	60	60	60	70	70	62
Lines of trees	21	31	21	35	25	32
Rows of trees	8	7	5	7	7	/
Average height (m)	6.4	3.2	6	5.3	4.5	12.5
DBH (cm)	6.6	5.4	7.8	8.5	8.3	11.4
Tree spacing (m)	3.0	2.0	3.0	2.0	2.0	2.3
Crown diameter (m)	2.7	2.2	4.5	2.3	2.5	2.3

As shown in Table 3, the MCBLF had the highest average mass density (1.21 kg m^{-3}) and crown volume (40.3 m^3). The sample average mass of the MCBLF was 8.1g. *I. chinensis* Sims followed, with an average mass density of 1.17 kg m^{-3}. It had a compact crown structure and significant height under the branch (2.5 m), making it effective at reducing noise from higher locations. *P. serrulate* Lindl. followed this, although it had the smallest crown volume (3.2 m^3) and height under the branch (0.7 m), keeping an average mass density in the middle level (1.01 kg m^{-3}). *C. deodara* (Roxb.) G. Don., *Z. serrata* (Thunb.) Makino, and *P. cerasifera* Ehrhar f. had lower mass densities. The height under the branch of *C. deodara* (Roxb.) G. Don. was only 0.8 m. *Z. serrata* (Thunb.) Makino, despite its larger crown volume (22.1 m^3), had a relatively low mass density (0.9 kg m^{-3}). *P. cerasifera* Ehrhar f. had a small crown volume and the lowest average mass density in all forests, only 0.86 kg m^{-3}.

Table 3. Other characteristics of road shelter forests.

Forest Belt Type	Average Mass M_0 (g)	Height under Branch (m)	Crown Volume (m^3)	Average Mass Density (kg m^{-3})
C. deodara (Roxb.) G. Don.	12.03	0.80	10.68	0.97
P. serrulate Lindl.	9.51	0.70	3.17	1.01
Z. serrata (Thunb.) Makino	5.00	2.00	22.14	0.90
I. chinensis Sims	9.02	2.50	6.37	1.17
P. cerasifera Ehrhar f.	5.85	1.10	6.16	0.86
MCBLF	8.05	2.30	40.29	1.21

Note: The sample volume is 8000 cm^3.

Table 4 showed that after standardized calculation, the average mass surface density of shelter forest types had a relatively stable trend at different widths of belts. Despite the increase in belt width, the average mass density remained unchanged.

Table 4. Average mass surface density $\overline{m}$ (kg m^{-2}) of road shelter forests.

Forests Width (m)	*C. deodara* (Roxb.) G. Don.	*P. serrulate* Lindl.	*Z. serrata* (Thunb.) Makino	*I. chinensis* Sims	*P. cerasifera* Ehrhar f.	MCBLF
10	0.98	1.01	0.90	1.17	0.86	1.13
20	0.98	1.02	0.90	1.17	0.87	0.96
30	0.98	1.01	0.90	1.17	0.86	1.10
40	0.98	1.01	0.90	1.17	0.86	1.13
50	0.98	1.01	0.90	1.17	0.86	1.18
60	0.98	1.01	0.90	1.17	0.86	1.25

The original data are the cumulative mass surface density under different width belts. To convert these data to standardized average mass surface density, we divide the cumulative surface density by the corresponding width to obtain a standardized surface density per 10 m of width.

3.2. Effects of Shelter Forests' Characteristics on Noise Reduction

3.2.1. Influence of Forest Width on Noise Reduction

According to Table S2, the MCBLF showed the best noise reduction effects (r = 0.98) (Figure 5f) at a width of 60 m, with an additional noise reduction of 6.6 dB(A). The noise reduction effects of *I. chinensis* Sims and *P. serrulate* Lindl. also showed relatively strong effects at the same width, with an additional noise reduction of 6.0 dB(A) and 5.7 dB(A), respectively. By contrast, *P. cerasifera* Ehrhar f. demonstrated the weakest noise reduction capacities. The additional noise reduction was only 4.9 dB(A) at a width of 60 m. However, there was a significant correlation between forest width and noise reduction effects (r = 0.89, $p < 0.05$) (Figure 5). The noise reduction effects of *C. deodara* (Roxb.) G. Don. fluctuated across different forest widths, about 5.6 dB(A) at the width of 50 m. The noise reduction effects did not increase with the increase in shelter forest width after 50m. All in all, the six types of shelter forests showed a significant positive correlation between forest width and noise reduction ($p < 0.05$) (Figure 5).

3.2.2. Influence of Average Forest Height on Noise Reduction

Comparative analysis of shelter forest characteristics between the Third Ring Road and National Highway 312 (Table 2 and Table S1) inferred that, taller forests generally had stronger noise reduction effects. Although the correlation between average forest height and noise reduction was not statistically significant ($p > 0.05$), the high correlation coefficient (r = 0.76) still indicated that average forest height played a role in noise reduction. However, this was not a crucial influencing factor (Figure S1).

3.2.3. Influence of Shelter Forest Structure and Type on Noise Reduction

Table 2 and Table S3 show that the type and structure of shelter forests had a significant impact on noise reduction. The MCBLF, which had a more complex structure, reduced more noise than PFs. For example, at a forest belt width of 60 m, the MCBLF reduced additional noise by 6.6 dB(A), while the average additional noise reduction in PFs was 6.3 dB(A). The MCBLF was the best option for reducing noise across all forest belt widths. However, the noise reduction effects of other shelter forest structures varied with forest belt widths. When the belt width was more than 30 m, evergreen broad-leaved PFs reduced additional noise much better than evergreen needle-leaved PFs. For example, at a 60 m belt width, *C. deodara* (Roxb.) G. Don. reduced additional noise by 5.5 dB(A), while *I. chinensis* Sims reduced noise by around 6.0 dB(A). Deciduous broad-leaved PFs, like *P. cerasifera* Ehrhar f., had weaker additional noise reduction effects (about 4.9 dB(A) at a 60 m width) compared to evergreen broad-leaved PFs like *I. chinensis* Sims. In summary, evergreen broad-leaved PFs were the optimal choice for noise reduction in PFs when the belt width exceeded 30 m. But when the belt width was less than 30 m, deciduous broad-leaved PFs reduced additional noise the most out of all the PFs. For example, *P. serrulate* Lindl. reduced additional noise by 4.9 dB(A) at a belt width of 30 m, followed by evergreen broad-leaved PFs (*I. chinensis* Sims) and evergreen needle-leaved PFs (*C. deodara* (Roxb.) G. Don.), which reduced noise by 4.7 and 4.4 dB(A), respectively.

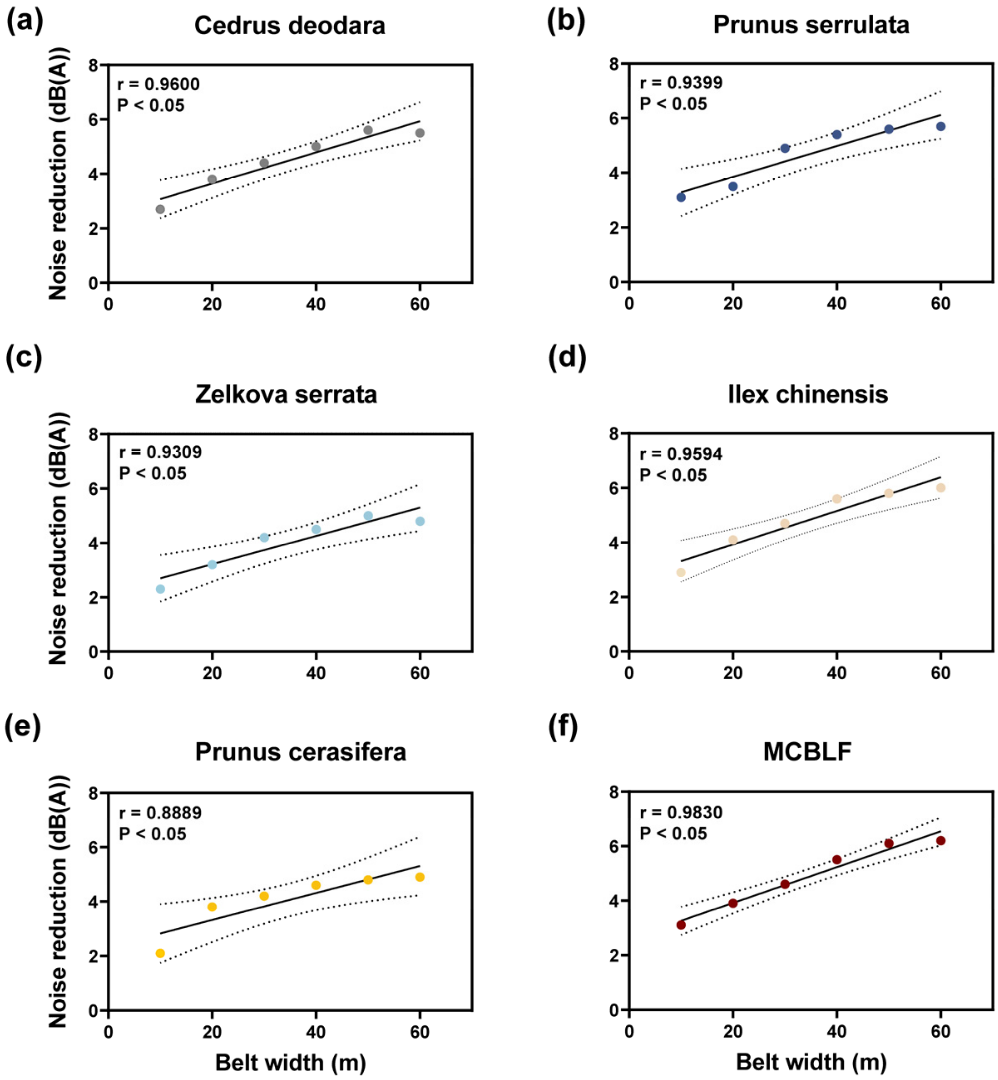


Figure 5. Noise reduction effects of six different forest species at belt widths. Each chart (**a**–**f**) showed noise reduction (dB(A)) for different forest belts (*Cedrus deodara* (Roxb.) G. Don., *P. serrulat* Lindl., *Zelkova serrata* (Thunb.) Makino, *Ilex chinensis* Sims and *Prunus cerasifera* Ehrhar f., and mixed coniferous broad-leaved forest (MCBLF)) across a width range of 10 to 60 m. The correlation coefficient (r) reflects the protective effectiveness of each species.

3.2.4. Influence of Crown Shape on Noise Reduction

Table S1 and Table 2 showed that the crown shapes of the six types of shelter forests were different. The analysis between crown shape and the additional noise reduction revealed that the mixed shapes and conical crown shapes had the highest median noise reduction values, approaching 7.0 dB(A). The mixed crown and conical crown shapes were most effective in weakening noise. By contrast, inverted conical crown and near-spherical crown shapes had lower median values (6.0 dB(A)). The noise reduction effect was more concentrated, and there was less variability (Figure 6). To achieve optimal noise reduction effects, crown shapes may need to be combined with suitable average mass density.

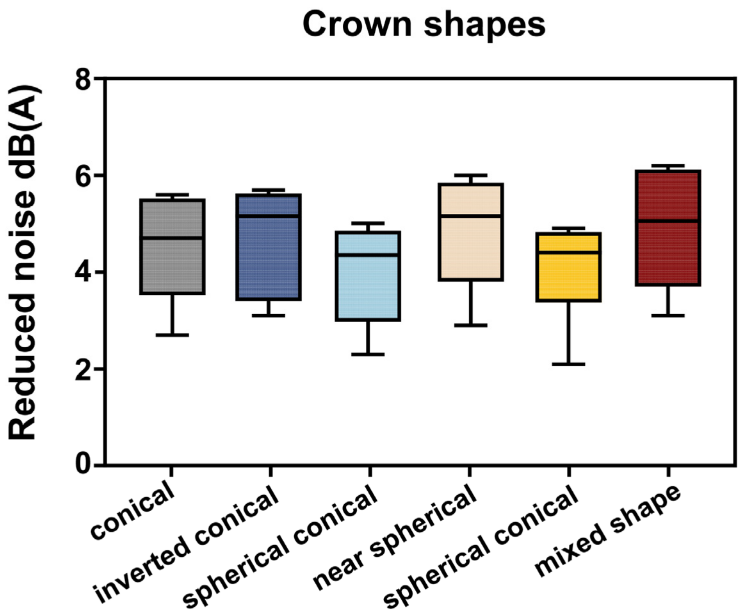


Figure 6. The impact of different crown shapes on noise reduction. The distribution of noise reduction effects (dB(A)) across six crown shapes, including conical, inverted conical, spherical conical, near-spherical, and mixed shapes.

3.2.5. Influence of Average Mass Density on Noise Reduction

As shown in Table 3, the average mass density of the MCBLF was the highest, at 1.21 kg m^{-3}. This forest was made up of eight different tree species, with a complex structure, large crowns, and maximum noise reduction potential (Table 2). *I. chinensis* Sims followed closely, with an average mass density of 1.17 kg m^{-3}. *I. chinensis* Sims had a near-spherical crown, compact structure, and higher under branch height, which led to more noise reduction. By contrast, *P. serrulate* Lindl. and *Z. serrata* (Thunb.) Makino had lower average mass densities of 1.01 kg m^{-3} and 0.90 kg m^{-3}, respectively. These trees had more dispersed crown structures and larger tree spacing (Table 2). Figure 7 showeed that average mass density was one of the important factors for reducing noise. With the increase in forest width, the noise reduction showed an increasing trend. There were positive relationships between average mass density and noise reduction at forest widths of 10 m, 40 m, 50 m, and 60 m ($p < 0.05$). The correlation coefficients for all these widths were higher than 0.8 (0.83, 0.91, 0.94, and 0.96, respectively). However, at widths of 20 m and 30 m, the noise reduction benefits were lower than other widths and not statistically significant ($p > 0.05$).

3.2.6. Influence of Cumulative Mass Surface Density and Additional Noise Reduction

Table S1 and Table 4 revealed that increased forest width led to higher cumulative mass surface density and improved noise reduction effects. At a width of 60 m, the cumulative mass surface density of MCBLF was 75.1 kg m^{-2}, and the corresponding additional noise reduction was 6.6 dB(A). *I. chinensis* Sims also demonstrated significant noise reduction effects at the same belt width (6.0 dB(A)). Its cumulative mass surface density was 70.0 kg m^{-2}. Linear regression analysis confirms that cumulative mass surface density was another important factor of noise reduction ($p < 0.01$, $R^2 = 0.93$) (Figure 8). Generally, higher average mass density meant higher cumulative mass surface density, which represented better noise reduction effects. Different types of shelter forests might have achieved optimal noise reduction at specific mass surface densities. Once this specific mass surface density was exceeded, the noise reduction benefit did not increase and reached saturation.

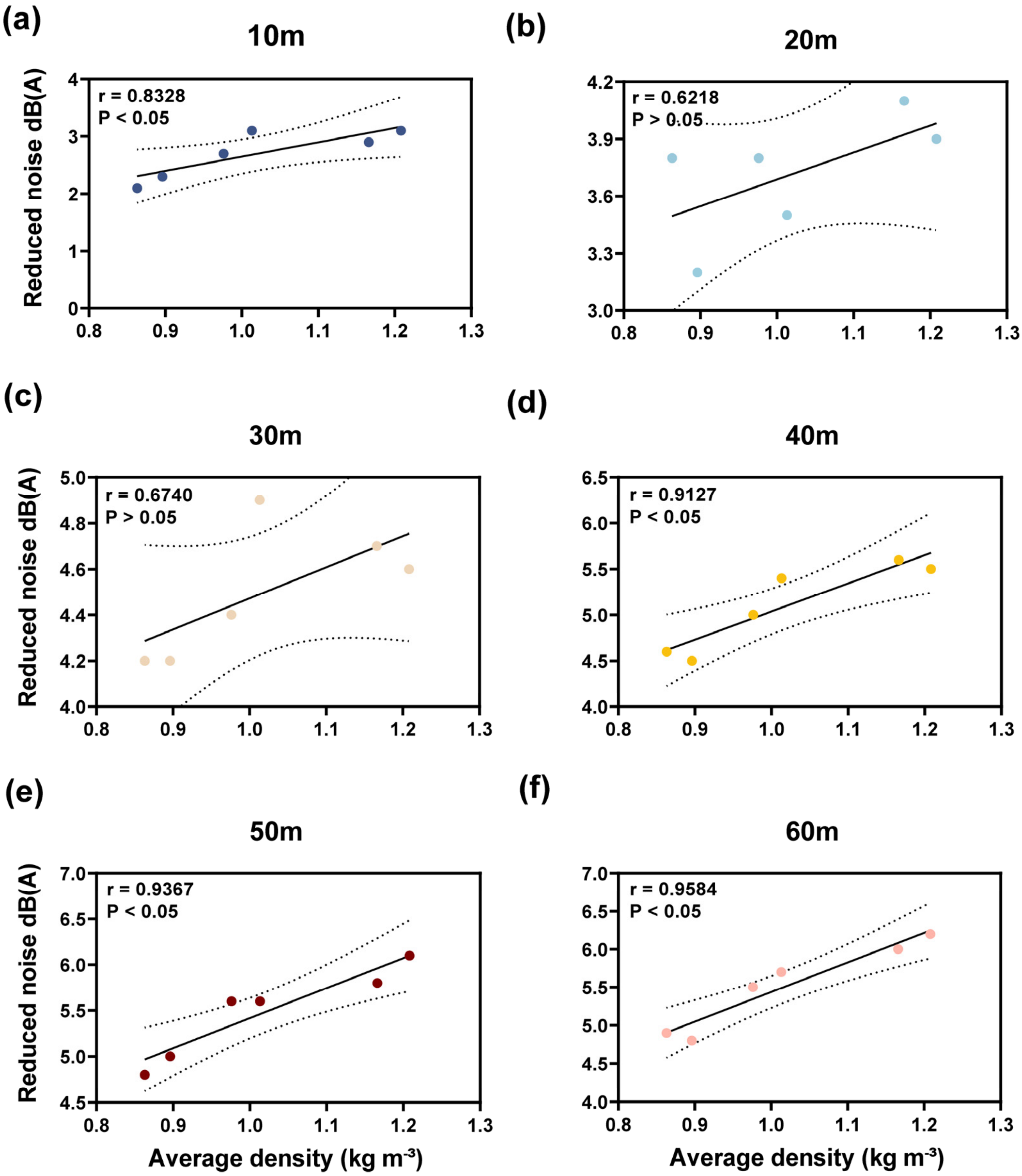


Figure 7. Correlation analysis between the average mass density of different shelter forest types and noise reduction effects at various belt widths. Charts (**a**–**f**) display the correlation between average mass density (kg m^{-3}) and noise reduction effects (dB(A)) at 10 m, 20 m, 30 m, 40 m, 50 m, and 60 m, respectively. Correlation coefficients (r) and significance levels (*p*-values) are shown in the charts.

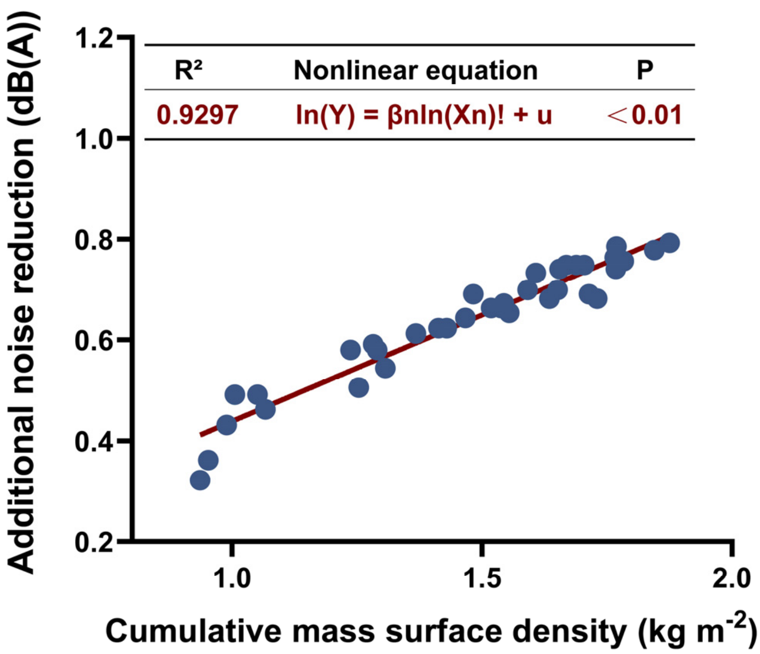


Figure 8. Linear regression analysis of the relationship between cumulative mass surface density (kg m^{-2}) of shelter forest and additional noise reduction (dB(A)). The goodness of fit was $R^2 = 0.93$, $p < 0.01$, indicating a significant positive impact of average surface density on noise reduction. Each point in the figure represents the additional noise reduction effect of the shelterbelt and its cumulative mass surface density. The regression line represents the nonlinear fitting result.

3.3. Noise Reduction at Different Frequencies by Shelter Forest Width

Figure 9a showed that noise reduction at a width of 20 m varied significantly across different frequencies. In general, the 20 m width was least effective at reducing low-frequency (31.5 Hz, 63 Hz) and high-frequency (4000 Hz, 8000 Hz) noise. The noise reduction values of all forest types were between 0.7 dB(A) and 1.5 dB(A). The MCBLF showed the strongest noise reduction at mid-frequencies (250 Hz, 500 Hz), exceeding 2 dB(A). Other forest types also demonstrated optimal noise reduction effects at 500 Hz. *C. deodara* (Roxb.) G. Don. was the best at 2000 Hz, reducing noise by 2.2 dB(A), and *P. serrulate* Lindl. performed best at 4000 Hz and 8000 Hz, reducing noise by more than 1.5 dB(A).

At a width of 40 m, noise reduction improved at all frequencies, especially for low- and high-frequency noises (Figure 9b). The MCBLF showed the highest noise reduction at mid-frequencies as well, reducing over 3 dB(A) at 500 Hz. *P. serrulate* Lindl. maintained strong noise reduction at 2000 Hz and 4000 Hz (3 dB(A)). At 8000 Hz, *Z. serrata* (Thunb.) Makino and *I. chinensis* Sims also reduced noise well, by about 2.5 dB(A). In general, the 40 m width of forests showed a more balanced noise reduction effect in most frequency ranges. The noise reduction effect became more significant as the frequencies increased.

At a width of 60 m, all shelter forests had the best noise reduction effects (Figure 9c). The MCBLF reduced noise by 5 to 5.5 dB(A) at 250 Hz and 500 Hz. At 1000 Hz and 2000 Hz, *P. serrulate* Lindl. continued to reduce noise well, by about 4.5 dB(A). Unlike the previous two belt widths, in the high frequency range (4000 Hz, 8000 Hz), the noise reduction effects of MCBLF were most effective, reducing noise by about 4 dB(A).

In summary, with the increase in forest width, the noise reduction effect of shelter forests was enhanced in all frequency ranges, especially in the mid- and high-frequency ranges. The noise reduction effect of the forest belt reached the maximum at 60 m, especially for the frequency of 250–1000 HZ. Additionally, shelter forests reduced high-frequency noise (like 4000 Hz and 8000 Hz) better than low-frequency noise.

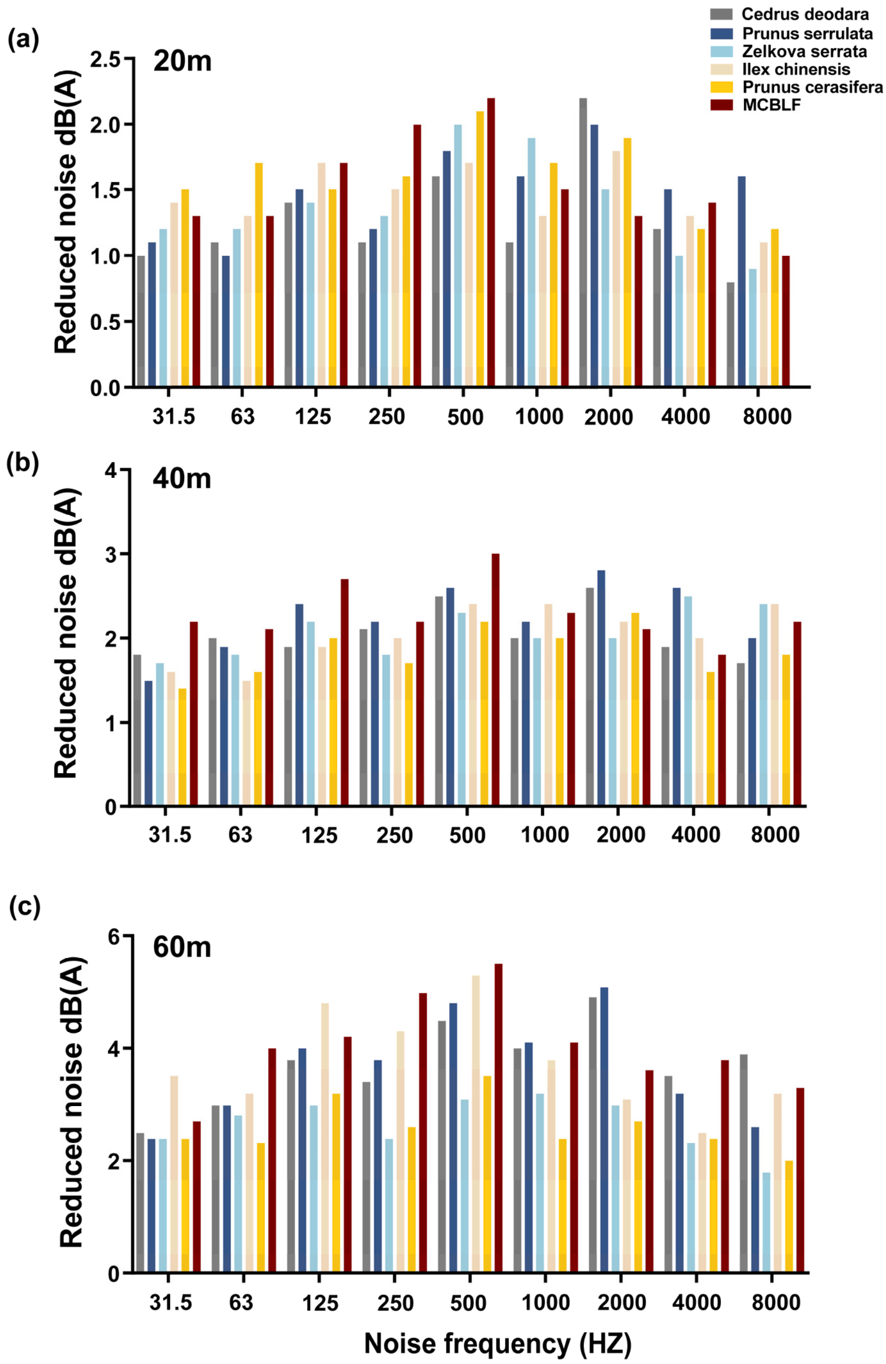


Figure 9. Noise reduction effects of different shelter forest types at (**a**) 20 m, (**b**) 40 m, and (**c**) 60 m forest widths across various noise frequencies, across a frequency range from 31.5 Hz to 8000 Hz.

3.4. Economic Benefits of Shelter Forest on Noise Reduction

With the increase in forest belt width, the noise reduction value per unit area for six shelter forest types showed a declining trend (Figure 10). As the width of the forest belt increased, the noise reduction value per unit area decreased, and the costs of planting and maintaining the shelter forests rose. When the forest belt was wider than 10 m, the costs became higher than the ecological, social, and economic benefits. This caused the economic benefit per unit area of the shelter forest to decrease. Additionally, the noise reduction value per unit area peaked at a width of 10 m, with the MCBLF achieving the highest (2937 RMB hm^{-2} yr^{-1}). Additionally, *I. chinensis* Sims also showed a significant economic benefit for PFs with approximately 2073 RMB hm^{-2} yr^{-1} and with a belt width of 10 m. The minimum economic benefit of all shelter forest belts with a width of 60 m reached about 1100 RMB hm^{-2} yr^{-1}. This shows a higher noise reduction value per unit area only at narrower forest belt widths (Figure 10).

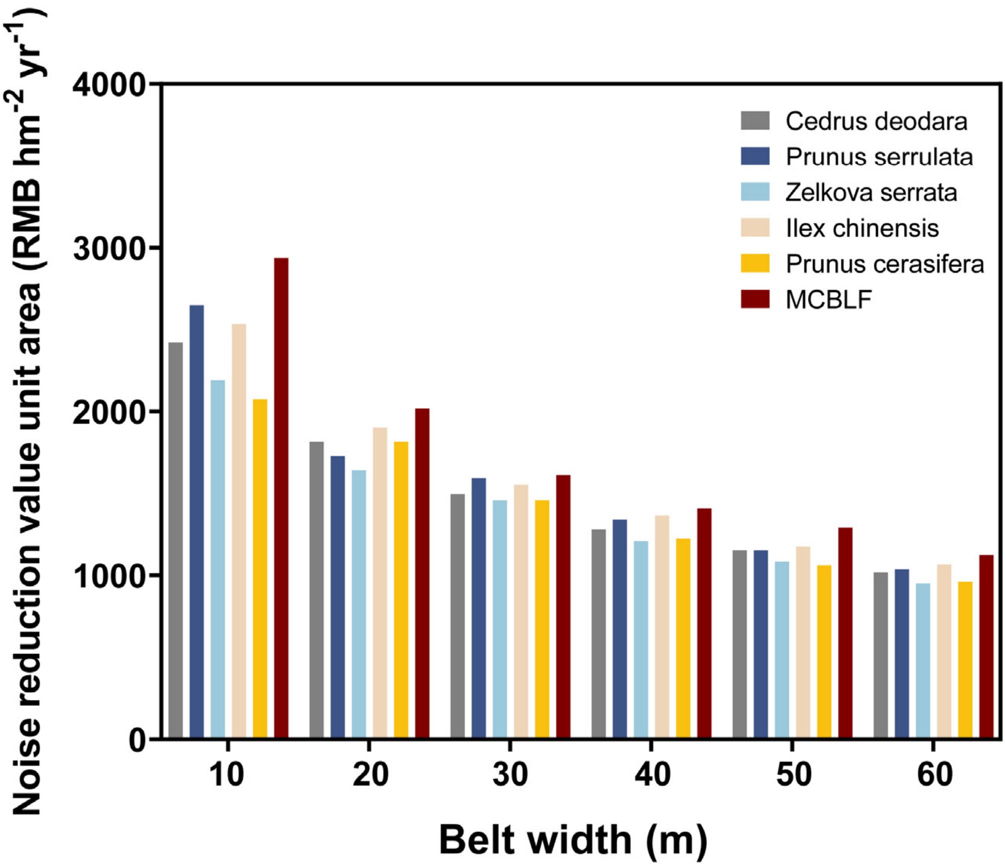


Figure 10. The economic value per unit area of noise reduction (RMB hm^{-2} yr^{-1}) for shelter forest types at various belt widths (The R_t used to calculate the economic benefits are shown in Table S3.).

The economic benefits of *C. deodara* (Roxb.) G. Don. ranged from 1300 to 2000 RMB hm^{-2} yr^{-1}. Most of the values were around 1600 RMB hm^{-2} yr^{-1}, as shown in the histogram. The frequency curve was symmetrical, which meant the economic benefits were quite stable (Figure 11a). By contrast, *P. serrulate* Lindl. had a wider range of economic benefits, mostly around 1500 RMB hm^{-2} yr^{-1}. However, the histogram distribution was more dispersed, showing more variation in economic benefits (Figure 11b). For *I. chinensis* Sims, the economic benefits were between 1200 and 1800 RMB hm^{-2} yr^{-1}, meaning its benefits were lower. However, the distribution range was narrower, and the histogram was more compact, showing highly concentrated results and better curve fitting. This made *I. chinensis* Sims the most stable in economic benefits (Figure 11d). *Z. serrata* (Thunb.) Makino and *P. cerasifera* Ehrhar f. had similar economic benefit patterns to *C. deodara* (Roxb.) G. Don., with symmetrical curves and good stability. The economic benefits for these two species ranged from 1300 to 2200 RMB hm^{-2} yr^{-1}, providing higher economic returns compared to other PFs (Figure 11c,e). Finally, the MCBLF had the widest range of economic benefits and the highest values, with most around 1900 RMB hm^{-2} yr^{-1}. Although the histogram was relatively compact, it showed irregular changes, indicating high variability and risks (Figure 11f).

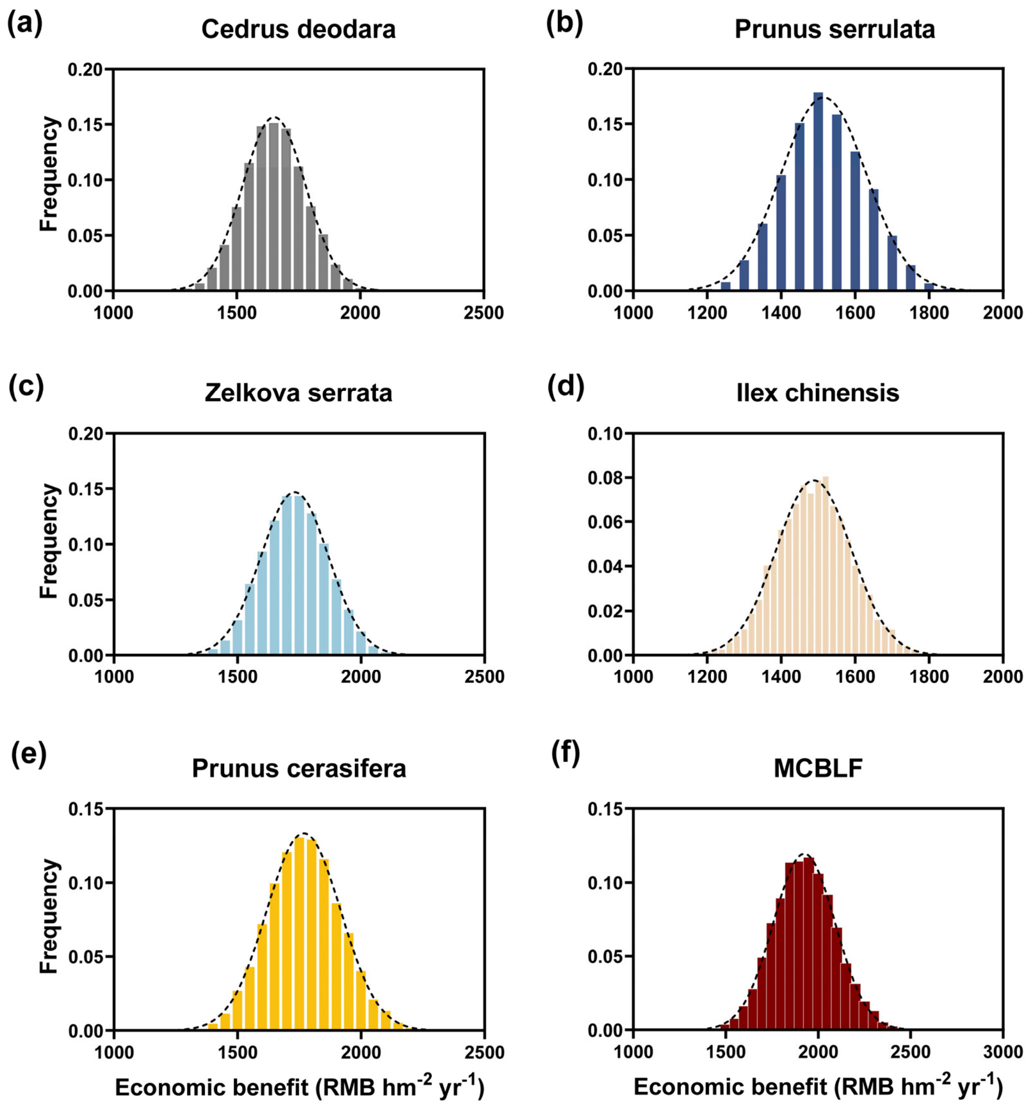


Figure 11. Relative frequency distribution of economic benefits per unit area for different shelter forest belts based on the Monte Carlo model. Each subplot represents the relative frequency distribution of economic benefits for (**a**) *C. deodara* (Roxb.) G. Don., (**b**) *P. serrulate* Lindl., (**c**) *Z. serrata* (Thunb.) Makino, (**d**) *I. chinensis* Sims, (**e**) *P. cerasifera* Ehrhar f., and (**f**) the mixed coniferous broad-leaved forest (MCBLF). The X-axis represents economic benefits (RMB hm^{-2} yr^{-1}), and the Y-axis represents relative frequency. The black dashed line is the fitted probability density curve.

4. Discussion

4.1. Impact of Road Shelter Forest on Noise Reduction

This study showed a significant positive relationship between tree height, crown shape, forest structure, planting density, average surface mass density, and width with noise reduction effects. This finding was similar to Baldauf's results [46]. Research has shown that the structure of the forest and the size of leaves can help scatter sound waves near the source of noise [47]. When traffic noise passes through dense forests, taller trees offer a larger surface area to absorb and spread the sound [48]. Therefore, when trees reach a certain height, they can block the noise effectively [49]. Tree crowns also play a key role in reducing noise. Tree crown shapes and volumes can reflect, refract, and absorb sound waves, thus altering the noise propagation path to reduce noise [50]. The bigger and thicker the tree crown, the better the noise reduction [51]. We found that *C. deodar* (Roxb.) G. Don. had a conical crown shape, *Prunus serrulate* Lindl. had an inverted conical shape, and the MCBLF was composed of multiple species with diverse crown shapes forming a mixed crown structure. The MCBLF showed superior noise reduction effects (Table S3). Furthermore, the structure of the forest belt also affected noise reduction. Our findings showed that the MCBLF outperformed PFs in noise reduction (Table S2). The MCBLF consisted of multiple tree species with complex and large crowns and dense leaves (Table S1). The MCBLF have uneven height and multi-layered forest belt structure, those enhanced its ability to absorb and scatter traffic noise across different frequencies and heights, contributing to better noise dispersion and absorption [52]. By contrast, PFs had simpler crown shapes and uniform arrangement, which did not block low- and mid-frequency noise as well (Figure 9), which is consistent with Li's findings [53]. However, this result was contrary to the results of Wang et al., and it may be related to the planting density of the selected tree species [27]. Therefore, the density of tree planting also plays an important role [54]. Dense shelter forests can effectively block road traffic nois [39]. Additionally, in this study, shelter forests with higher average surface mass density showed stronger noise reduction capacity, a result also supported by Ow's research [55]. Thus, optimizing tree species combinations, adjusting surface mass density, and increasing the complexity of shelter forest structures are key to improving noise reduction efficiency. Finally, we found that the width of the forest belt had a significant impact on noise reduction. There was a notable connection between the width of the shelter forest and noise reduction (Figure 5). Our findings are consistent with studies by Lampartova and Huang et al. [56,57]. Previous research showed that traffic noise arrived at maximum reduction when passing through 60 m wide multi-layered shelter forests [31]. Our study confirmed this, as the MCBLF achieved the best noise reduction at a 60 m wide belt. For some PFs, like *C. deodara* (Roxb.) G. Don. and *Z. serrata* (Thunb.) Makino, maximum noise reduction happened at 50 m, and widening the forest belt beyond this did not result in more reduction (Figure 10). This was also seen in other research [58]. Additionally, there was a connection between the width of the shelter forest and the noise reduction at different frequencies (Figure 9) [30]. Shelter forests reduced noise below 2000 Hz (low- and mid-frequency noise) better than high-frequency noise (4000–8000 Hz) [59], with the best reduction at 500 Hz traffic noise, which matches Zhang's findings [60]. Although increasing the width of the forest belt improves noise reduction, the lack of space in cities due to population growth makes very wide forest belts impractical. Therefore, a good solution for urban planners is to combine narrower shelter forests with noise barriers, like sound walls. This approach offers urban planners a balanced noise reduction strategy. Future research can explore the effectiveness of such combinations in different environments and tree species arrangements to further enhance noise reduction effects.

4.2. Economic Benefits of Noise Reduction by Road Shelter Forest

Road shelter forests not only effectively reduced road noise and improved the climatic environment but also provided considerable economic benefits [61]. When the forest belt was 10 m wide, the annual economic benefits for each unit of area were the highest (Figure 10). When the forest belt became wider, the cost of building and maintaining became higher, which made the economic value for noise reduction per unit of area go down (Figure 10). Additionally, the MCBLF provided the highest economic benefits, especially when it was 10 m wide. This meant that a narrower MCBLF was the best option in areas with limited land resources. This result is similar to what Attenborough found, showing that the MCBLF is very useful for controlling noise from traffic in cities [20]. Further Monte Carlo simulations revealed that *C. deodara* (Roxb.) G. Don. and *Z. serrata* (Thunb.) Makino were relatively low-risk and high-return shelter forests, while *P. cerasifera* Ehrhar f. and the MCBLF showed relatively high returns, high volatility, and high risk. *P. serrulate* Lindl. and *I. chinensis* Sims offered stable returns with low economic volatility (Figure 11).

Road shelter forests are valuable both economically and ecologically. Their ecological benefits include many ecosystem services. These services include oxygen release, carbon sequestration, dust retention, and noise reduction [54]. A study from China showed that road shelter forests improved soil porosity, moisture content, and fertility, in addition to increasing air humidity and improving habitat conditions [62]. Currently, the assessment of the ecological benefits of road shelter forests is still being explored. It is very important to incorporate an ecosystem-protection-centered approach guided by climate change response policies, employing comprehensive ecosystem evaluation methods. These methods need to assess the benefits of shelter forests on both regional and local levels [16]. In addition, with the help of the right policy tools and based on current national policies, it is necessary to comprehensively evaluate the multiple ecosystem services of shelter forests [18].

4.3. Influence of Shelter Forest Noise Reduction on Residents

Traffic noise is an important problem in residential areas, impacting residents' lives. According to the National standard (GB3096-2008) [63], road traffic noise levels were divided into five levels (Table 5). Assuming our goal is to reduce noise from a high pollution level (74 dB(A)) to a superb level (68 dB(A)), this means that we need to reduce noise by at least 6 dB(A). Based on Table S3, we need to establish a shelter forest with a minimum width of 20 m and match appropriate forest species. As shown in Figure 10, the economic effects per unit area decreased with increasing width, and the MCBLF provided higher noise reduction benefits than the five types of PFs. Therefore, constructing a MCBLF of a 20 m width is the optimal choice for road noise reduction, under the premise of meeting national noise reduction standards. The 20 m forest belt width has a relative balance between benefits and costs. Nevertheless, the premise was still an optimal forest belt structure and configuration.

Table 5. Quality classification of road traffic noise equivalent sound level dB(A).

Noise Type	H-Pollution	M-Pollution	L-Pollution	Better	Superb
Leq (A)	>74.0	72.1~74.0	70.1~72.0	68.1~70.0	≤68.0

Notice: the original data came from the Chinese national standard (GB3096-2008).

4.4. Applicability of This Research

This study mainly focused on the noise reduction effects of urban road shelter forests under specific climatic conditions. First, although the correlation between tree crown shape, height, and surface mass density with noise reduction might have general applicability, tree growth patterns, density, and structure can vary under different climatic conditions [64]. Previous studies have shown that the noise reduction effects of shelter forests change with the climate and seasons [27]. For example, it was found that deciduous broad-leaved PFs had much greater noise reduction effects in summer compared to winter, while evergreen PFs had roughly the same effects across all seasons [65]. Therefore, based on the findings of this study, it is recommended to use mixed forests (including evergreen species) when designing urban road shelter forests to optimize noise reduction. Second, noise levels and frequencies are also affected by the volumes of traffic and types of vehicles. In areas with heavy traffic, especially where low-frequency noise is dominant, the noise reduction effect might weaken [66]. In such places, it is necessary to have wider and denser shelter belts near roads that are close to noise sources and residential areas. Additionally, combining shelter belts with artificial noise barriers, like berms or wooden walls, can further improve the noise reduction effect. Lastly, different types of vehicles produce different kinds of noise. This study primarily focused on traffic noise as the primary research target. Future research may build upon our findings and arguments to further explore their applicability. In practical use, local climate conditions, geographic environment, traffic volume, and noise frequency should all be considered when choosing tree species and designing shelter belts. For instance, using multi-layered forest structures that include trees, shrubs, and ground cover plants can help absorb and reduce noise more effectively.

4.5. Limitations and Implications of This Study

Although this study provided useful insights into the noise reduction effects of road shelter forests, it still had some limitations and uncertainties. First, the research data used in this research mainly came from a specific area in Nanjing (two typical roads) and was observed during a specific time (midday peak hours) and season (spring). Second, this study focused on a particular type of shelter forest, so the findings may not apply to other types of shelter forests. Third, assuming irregular tree crowns as regular geometric shapes to calculate crown volume may have introduced some errors. Additionally, due to the transient and non-reproducible nature of traffic noise, this study did not implement repeated noise measurements, which could increase the uncertainty of the results. Furthermore, this study also did not consider other environmental factors, such as traffic volume and pavement types, which might have made the discussion of influencing factors incomplete. Finally, the economic benefit assessment relied on specific assumptions and models. Although the Monte Carlo simulation provided risk assessment, actual economic benefits may change due to market changes and policy adjustments.

Future research should focus on the following areas: (1) conducting repeated measurements to validate the results of this study; (2) using advanced technology to monitor the noise reduction effects of shelter forests in different climates and landscapes; (3) exploring the potential integration of shelter forests with other artificial noise reduction equipment to achieve cost savings and maximize multiple benefits; (4) studying the noise reduction effects of different tree species and how they perform under different environmental conditions; (5) introducing more ecological compensation policies and mechanisms to encourage the building and promotion of road shelter forests; (6) conducting comprehensive evaluations of the noise reduction, ecological services, and economic benefits of road shelter forests and exploring appropriate integrated evaluation methods.

5. Conclusions

This study showed that mixed coniferous broad-leaved forests (MCBLFs) have significant advantages in both noise reduction and economic benefits, making them the best choice for constructing road shelter forests. This type of forest provided substantial additional noise reduction, especially at a width of 60 m, where the reduction reached 6.6 dB(A). In terms of shelter forest width, a forest width of 60 m was most effective for noise reduction, especially for low- and mid-frequency noise. Factors like forest height, crown shape, average mass density, and noise frequency were positively correlated with noise reduction but were not the primary influences. The width of the shelter forests was the most important factor for traffic noise reduction. With the increase in the width of the shelter forests, the noise reduction was better. Additionally, cumulative mass surface density was another key factor in noise reduction ($p < 0.01$, $R^2 = 0.93$). The higher the surface mass density, the better the noise reduction effect. From an economic perspective, the MCBLF provided the highest economic benefits, outperforming pure forests (PFs). However, as the width of the forest belt increased, the annual economic benefit per unit area for noise reduction decreased. The economic benefits of all shelter forest types peaked at a width of 10 m. Although the noise reduction per unit area with a width of 10 m had the greatest noise reduction effect, noise reduction effects may not meet the national noise reduction standard (GB3096-2008). Therefore, based on the national standard, this study suggests a 20 m wide MCBLF as the ideal choice between noise reduction efficiency and costs. The findings of this study offer valuable scientific guidance for road shelter forest planning. Future research could explore the impact of the mixing of other tree species on noise reduction.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/f15101714/s1, Figure S1. Scatter plot and linear regression analysis between average tree height (m) and additional noise reduction value dB(A). Each point in the figure represents the average height of shelter forests and its additional noise reduction effect. The regression line indicated a positive correlation between them, but statistical analysis showed that the correlation did not reach significance (r = 0.7603, $p = 0.0793$); Table S1. Basic characteristics of the MCBLF on the east south side of G312. Table S2. The measured data of the additional noise reduction of shelter forests per 10 m Leq (A). Table S3. The measured data of the noise reduction of shelter forests per 10 m dB(A).

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