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Assessment of Urban Forest Ecological Benefit Based on the i-Tree Eco Model—A Case Study of Changchun Central City

Hongyu Zhao [1], Dongliang Zhao [2], Xue Jiang [1,*], Shiyu Zhang [1] and Zhanlue Lin [3]

[1] Urban Spatial Performance Assessment & Visualization & Decision-Making Laboratory in Cold Region, School of Architecture and Urban Planning, Jilin Jianzhu University, Changchun 130118, China; zhaohongyu@jlju.edu.cn (H.Z.); zhangshiyu@student.jlju.edu.cn (S.Z.)
[2] Shenzhen New Land Tool Planning & Architectural Design Co., Ltd., Shenzhen 518172, China; zhaodongliang@student.jlju.edu.cn
[3] Tong Cheng Urban Planning and Design Co., Ltd., Changchun 130022, China; 18626647276@163.com
* Correspondence: jiangxue@jlju.edu.cn; Tel.: +86-130-7432-1409

Abstract: Urban forests are one of the most ecologically significant systems in urban ecosystems. To make the layout and input–output ratio of urban forests more economically rational for sustainable strategic planning, it is necessary to assess the ecological benefits and ecosystem services of urban forests according to the local geographical characteristics of different cities and analyse their cost–benefit relationships. In this study, the i-Tree Eco model was used to assess the ecological benefits of urban forests in terms of four aspects: carbon sequestration and oxygen release, energy saving, rainwater retention, and air quality improvement. To translate them into economic benefits, using mathematical and statistical analysis, the cost–benefit relationship of urban forests with different tree and shrub proportions was analysed, and the impact range of urban forests with different layout types was compared. The research found that: (1) tree species are the main influencing factor of urban forest ecological benefits, (2) linear urban forests have a wider impact range, (3) if the proportion of trees in urban forests in the research area is adjusted to 0.36, the ecological benefits can increase by RMB 0.061 billion per year. We provide efficient and convenient research paths and tools for studying the cost–benefit relationship. By using an i-Tree Eco model, we realized the economic characteristics of urban forests. This research provides quantitative support for the balanced construction of urban ecological civilization and economic benefits. It can provide quantitative support for a balance between urban ecological development, economic development, and spatial optimization.

Keywords: urban forests; ecological benefits; ecosystem services; i-Tree Eco model

Citation: Zhao, H.; Zhao, D.; Jiang, X.; Zhang, S.; Lin, Z. Assessment of Urban Forest Ecological Benefit Based on the i-Tree Eco Model—A Case Study of Changchun Central City. *Forests* **2023**, *14*, 1304. https://doi.org/10.3390/f14071304

Academic Editor: Mike McKinney

Received: 16 May 2023
Revised: 22 June 2023
Accepted: 23 June 2023
Published: 25 June 2023

1. Introduction

Urban forests, as part of the forest ecosystem [1], are the sum of trees and shrubs within a city [2], and provide a large number of measurable ecological service values to the city [3]. Current studies on the ecological service value of urban forests mainly include the assessment of ecological benefits such as carbon sequestration and oxygen release [4], air quality improvement [5,6], cooling and humidification [7], noise reduction, energy saving [8], and rainwater retention [9]. The current methodological models such as carbon tax method [10] and CITYgreen model [11–13] used for urban forest ecological benefit assessment lack the use of climate and other data, which makes the assessment results less accurate. Meanwhile, studies on urban forest ecological benefit assessment are mostly conducted in cities in North America [10] and Europe [6,11], mostly in cities in the United States and the United Kingdom. As for Asia, the studies are mostly concentrated in the Kurdistan Region of Iraq [12], Abu Dhabi [13] in Arabia, and several cities with a warm climate in southern China, such as Nanjing [14,15], Hangzhou [16] and Qingdao [17]. There are very few studies focused on northern cities with a cold climate. Therefore, in this paper, by importing geoclimatic data from the central city of Changchun into the model (data on elevation, wind speed, rainfall, air pollution conditions, etc.), the accuracy of the modelling and technology-assisted assessment results is improved, while increasing the studies on urban forests in cold northern cities.

In this paper, the i-Tree (2021_6.1.36) model is adopted to assess the ecological benefits of urban forests. According to the review of domestic and international studies [18–21], there are two main models used for urban forest ecological benefits assessment: the i-Tree model and the CITYgreen model. The CITYgreen model was developed and applied earlier and is more commonly used, for example: the assessment of the ecological benefits of urban forest in Suzhou City [22], the assessment of the benefits of air purification and carbon sequestration and oxygen release from green areas in Shenzhen City [23], the assessment of the environmental services of trees in the open space of Yogyakarta International Airport [24]. The i-Tree model was applied later in China, for example: the assessment of the economic benefits of urban forests [25], the study of the effects of trees on urban quality, combining air monitoring and the i-Tree model [6], and the ecosystem assessment of urban green spaces in the UK [15]. However, the function module of the i-Tree model is more focused and able to assess the ecological benefits of different types of urban forests. Its study area can be as large as a city or as small as a courtyard, and the analysis results are highly accurate, although the data required is more complex.

Changchun has been called a 'Forest City' since the pseudo-Manchu period because of its rich forest resources. The central urban area of Changchun has a land area of 609.40 km^2 and a population of approximately 4.25 million people; as of 2019, the green coverage rate of the built-up areas in the region has reached 41%, with a per capita park green space of 14 m^2 [26]. However, after the founding of the People's Republic of China, Changchun, as a heavy industrial base of new China, vigorously developed industry and neglected urban ecological problems. The urban forest area in the central city was continuously encroached upon. In the 21st century, people have gradually realised the importance of urban ecology, and urban forests are gradually recovering, which provides good assessment conditions.

The objectives of this research are: (1) to import geoclimatic data from Changchun into the model to improve the accuracy, and then to compare the resulting ecological benefits for analysis; (2) to convert urban forest ecological benefits into economic benefits, and analyse its economic cost-ecological benefits relationship to provide an economical urban forest construction strategy for Changchun City; and (3) to obtain an optimal urban forest spatial layout and the optimal tree cover in residential areas through comparative analysis.

2. Materials and Methods

2.1. Research Data

2.1.1. Study Area

Changchun is located in a severely cold area with an annual average temperature of 4.6 °C, an average temperature of −15.1 °C in the coldest month (January), and an average temperature of 23.1 °C in the hottest month (July). The average annual sunshine time is 2688 h, the average annual rainfall is 576.1 mm, the frost-free period is 140–150 days, and the plant growth cycle is short, with distinctive regional climatic characteristics [27]. By 2019, the greening coverage rate of the built-up area of Changchun City reached 41%, and park green space 14 m^2 per capita [28], with good basic conditions for assessing the ecological benefits of urban forests.

2.1.2. Data Acquisition and Processing

Urban forests are the sum of trees and shrubs within the city. Accordingly, common tree and shrub species in Changchun City were selected as the source of data analysis. First, statistical analysis was conducted based on the results of the tree species and shrub species inventory in residential areas [29] and parks in Changchun [30], see Appendix A. Tree species and shrub species with planting frequencies greater than 60% were selected as experimental materials for this urban forest ecological benefit assessment. A total of

33 common woody species in Changchun were selected, including 20 tree species and 13 shrub species.

To get the evaluation results of the ecological benefits of transformation of urban forests, the i-Tree Eco model was adopted in this research. The calculation process involves the conversion of benefits from energy saving, carbon sequencing and oxygen release, air quality improvement, and rainwater retention (see Section 2.2.2). A random sample inventory of urban forest trees and shrubs in the central city of Changchun was conducted. Thirty-seven circular sample plots of about 400 m^2 were investigated according to the requirements, and data of 1026 tree and shrub individuals were obtained.

The inventory mainly included data of tree and shrub diameter at breast height (the diameter of a tree or shrub measured at breast height, which is typically at 1.3 m above the ground), total tree height (the vertical distance from the base of the tree to the highest point of the tree, including the crown), height of live trees (the vertical distance from the base of the tree to the highest point of the tree, excluding the crown), height of base crown (the height at which the lowest branches of the tree or shrub start), north–south crown width (the horizontal distance from the northern edge to the southern edge of the tree or shrub's crown) and east–west crown width (the horizontal distance from the eastern edge to the western edge of the tree or shrub's crown). The ecological benefits ratio of trees and shrubs are calculated as an estimate, which is used to help government make more reasonable decision judgments. Since this process does not involve specific planting plants, the method of average estimation was adopted individually, and the weighted average of tree and shrub species data were acquired separately (as in Table 1).

Table 1. Research data on common tree and shrub species in urban forests.

Categories	Average Diameter at Breast Height (cm)	Average Total Tree Height (m)	Average Height of Live Trees (m)	Average Height of Base Crown (m)	Average North–South Crown Width (m)	Average East–West Crown Width (m)
Trees	22.35	12.23	12.23	3.46	7.35	6.58
Shrubs	6.6	4.52	4.52	1.09	2.41	2.32

2.2. Research Methods

2.2.1. Outline

The outline of the study in this paper is shown in Figure 1. First, geoclimatic data such as elevation, area, population, frost-free period, and average annual temperature of the study area were submitted to the i-Tree Eco model in advance. Then the data was imported into the new version of the model before it could be used. During the use of the model, the Longjia Airport Weather Station in Changchun City was first selected as the meteorological data support for this study, and then a plot of sample area (400 m^2) was set, and trees and shrubs were stratified. Subsequently, in order to compare the differences in benefit creation among different tree species, including rainwater interception, carbon sequestration and oxygen release, air quality improvement, and energy conservation, we investigated sample area and obtained data on 1026 tree and shrub individuals. The data includes diameter at breast height, total height of trees, height of live trees, height of crown base, north–south crown width, east–west crown width, crown loss rate, crown death rate, and crown transparency. Some were incorporated with their weighted average, including diameter at breast height, total tree height, live tree height, basal crown height, north–south crown width, and east–west crown width, and the other data were incorporated with the individual data.

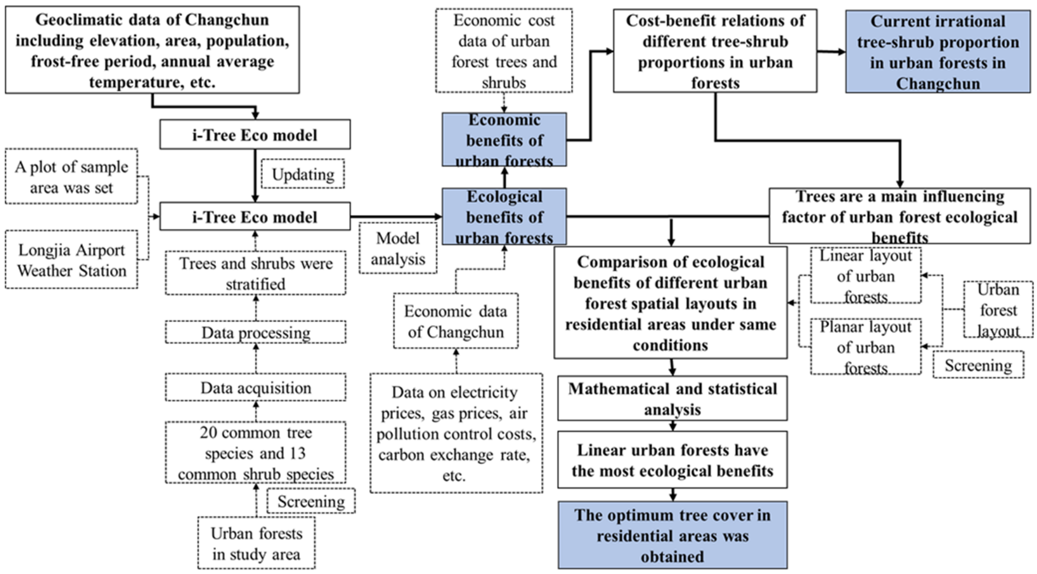

Figure 1. Block diagram of the study.

To convert ecological benefits into economic benefits, economic data (data on electricity prices, gas prices, air pollution control costs, etc.) needed to be set according to the actual situation; model defaults were used for data that are not priced, e.g., carbon exchange rate and rainwater runoff avoidance prices (Figure 2). Finally, according to the model calculation results, the average annual ecological benefits of common trees and shrubs in Changchun urban forests were derived.

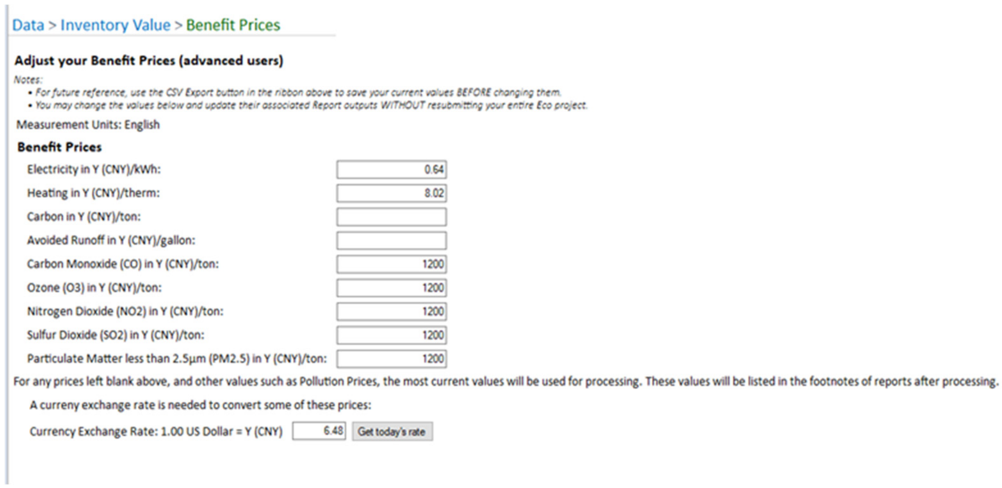

Figure 2. Economic data setup.

To compare and analyse the relationship between the economic cost and annual benefits of urban forest in different spatial layouts, residential land with an area of 1 ha was selected and calculated at the residential greening rate of 35% or higher. The proportion of trees and shrubs were divided by a difference of 5% for each level, and their economic costs and annual benefits were calculated separately.

In order to analyse the spatial layout of urban forest with optimal ecological benefits, two types of spatial layouts of urban forest with more obvious ecological benefits, linear (column planting, forest belt) and planar (group planting, forest planting), were selected by combining the results of ecological benefit assessment of common trees and shrubs in urban forest, and the advantages and disadvantages of ecological benefits generated by both were analysed in the method of controlling variables.

First, the same number of plants were arranged in the same land area. However, the comparison of the annual ecological benefits of trees and shrubs reveal that the average single plant annual ecological benefit of shrubs is only 0.04 of that of trees. The energy saving benefit for constructions is negative, and the ecological benefit improvement for urban forest is negligible, hence a comparative analysis was conducted by replacing plants with the same number of trees.

As shown in Figures 3 and 4, the same number of trees were laid out in a 1 ha plot in a linear and a planar pattern, respectively. Based on the calculation principle of energy saving benefit of the i-Tree Eco model, the influenced range of the plants on constructions is 3–18 m. Hence the influenced range of urban forest for the two spatial layouts are obtained separately, being 6402.49 m^2 in the planar layout and 15,388.40 m^2 in the linear layout.

$$\text{Tree coverage} = \frac{\text{sum of canopy projection area}}{\text{total residential area}} \times 100\% \quad (1)$$

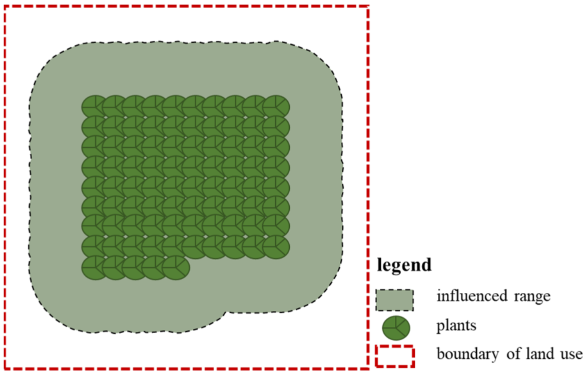

Figure 3. Diagram of the spatial layout of the faceted urban forest.

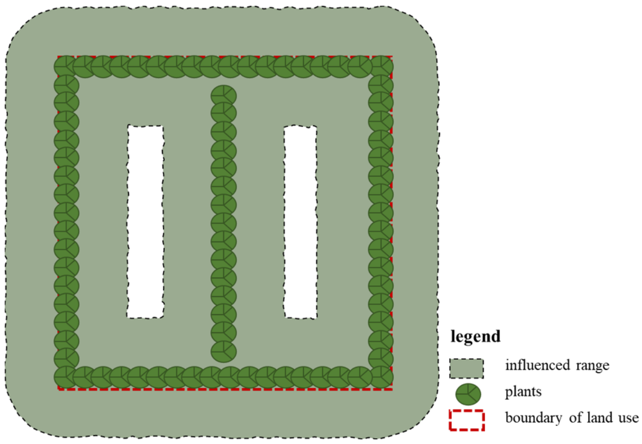

Figure 4. Illustration of the spatial layout of the linear urban forest.

By using the method of mathematical and statistical analysis, the influence of different tree–shrub proportions on the relationship between economic cost and annual benefit of urban forest construction was analysed, and the optimum tree–shrub proportion was achieved with the most suitable cost–benefit relationship. Finally, the results were analysed to get the optimal urban forest spatial layout pattern by arranging the same number of urban forests in the same area but with different spatial layout patterns.

2.2.2. Operation Principle of the i-Tree Eco Model

The i-Tree Eco model was used to assess the ecological benefits of urban forests in terms of four aspects: carbon sequestration and oxygen release, rainwater retention, energy saving, and air quality improvement. The model's algorithms and principles are shown in Table 2.

Table 2. Operation principle of i-Tree Eco model ecological benefit assessment.

<table>
<tr><th>Ecological Benefits</th><th>Impact Factor</th><th>Calculation Method</th><th>Base Price</th></tr>
<tr><td rowspan="2">Energy saving benefit</td><td>Leaf area index</td><td rowspan="2">Based on the amount of electricity and natural gas consumed to reduce or increase the same temperature as the tree community</td><td>Electricity</td></tr>
<tr><td>Canopy cover</td><td>Gas</td></tr>
<tr><td rowspan="3">Carbon sequestration and oxygen release benefit</td><td>Chest diameter distribution</td><td rowspan="3">Based on carbon tax on the same amount of carbon dioxide from direct carbon storage and indirect carbon reduction, and the total amount of oxygen generated</td><td>Carbon tax</td></tr>
<tr><td>Canopy cover</td><td rowspan="2">Oxygen</td></tr>
<tr><td>Tree growth</td></tr>
<tr><td rowspan="2">Air quality improvement benefit</td><td>Tree species</td><td rowspan="2">Based on taxes on direct absorption, indirect abatement and BVOC emissions of the same amount of air pollutants</td><td rowspan="2">Air pollution tax</td></tr>
<tr><td>Canopy cover</td></tr>
<tr><td rowspan="3">Rainwater retention benefit</td><td>Annual rainfall</td><td rowspan="3">Annual government funding for rainwater and erosion management based on the same amount of rainwater that is directly retained by the tree canopy and indirectly protected for water quality and flood control</td><td rowspan="3">Government funding for rainwater management</td></tr>
<tr><td>Leaf area index</td></tr>
<tr><td>Canopy cover</td></tr>
</table>

The i-Tree Eco model was used to calculate the benefits of carbon sequestration and oxygen release of urban forests based on tree growth models and is related to tree species, DBH, canopy size, and growth. The i-Tree Eco model first estimated the ecological benefits of carbon sequestration and oxygen release in urban forests. Then, based on the estimated CO_2 uptake and O_2 production and combined with the carbon tax standards and the price of O_2, it worked out the economic value of the urban forests in terms of carbon sequestration and oxygen release [31] through the substitution method.

The calculation of rainwater retention benefits in urban forests using the i-Tree Eco model required a combination of annual rainfall and economic data for the study area and was closely related to the leaf area and canopy size of the trees. The model's calculation of rainwater retention benefits focused on retention, but also involved transpiration and infiltration processes. Rainwater retention benefits were calculated using the following Equation (2) [9].

$$I = C + E = P - TH - D \tag{2}$$

where: I (mm) is the interception.

C (mm) is the amount of water held by the leaves.
E (mm) is the amount of water evaporated from the leaves.
P (mm) is the amount of rainfall.
TH (mm) is the amount of rainfall penetrated.
D (mm) is the amount of rain dripping from the leaves.

Based on the amount of money invested annually by the local government to protect public facilities from flood damage, the amount of money needed to capture the rainwater runoff from the urban forest was calculated, and the ecological benefits of rainwater retention from the urban forest were finally obtained and translated into economic benefits.

The energy saving benefits of the urban forest influence energy consumption mainly through the shading of the building by the trees, providing evaporative cooling, and blocking cold winter winds. It all depends on the distance of the trees from the building. In the i-Tree Eco model, when the trees were 3–18 m away from the building, there was an energy saving benefit for the first and second floors of the building [32]. The i-Tree Eco model calculated the energy saving benefit of the urban forests by calculating the amount of electricity and natural gas consumed to reduce or increase the same temperature, and finally, based on the price of electricity and natural gas, converted it into economic value.

Urban forests are able to absorb gaseous pollutants such as NO_2, SO_2, O_3, VOC, PM2.5 and PM10 from the air to improve air quality and provide fresh air. The i-Tree Eco model was used to calculate the air quality improvement benefits by calculating the rate of pollutant removal by trees with the following Equation (3) [33].

$$F = V_d \times C \quad (3)$$

where:

V_d (m/s) is the settling velocity of the gaseous pollutant.
C (g/m^3) is the concentration of the gaseous pollutant.

The total amount of air pollutants removed by urban forests was finally attained, and the economic value of air quality improvement by urban forests was calculated based on the funds invested by the government for air quality improvement through the substitution method.

3. Results

3.1. Analysis of Rainwater Retention Benefit of Urban Forests

During rainfall, a portion of the rainfall is intercepted by vegetation while another portion reaches the ground. The portion that reaches the ground partially infiltrates into the soil and the remainder forms surface runoff [34]. In the process of urbanisation, impervious surfaces increase on a large scale, leading to increased surface runoff. The leaf surfaces of trees and shrubs in urban forests can reduce surface runoff by trapping and storing rainwater, and their root systems can contribute to the infiltration rate of rainwater from the soil, thereby reducing surface runoff [35].

After calculation and analysis (as shown in Table 3), the rainwater retention benefit of 20 common tree species in Changchun was 95.78 m^3/year, generating an economic value of RMB 1467.24/year, with an average single tree rainwater retention benefit of 4.79 m^3/year. The rainwater retention benefit of 13 common shrub species in Changchun was 2.63 m^3/year, generating an economic value of 40.34 yuan/year, with an average single shrub water retention benefit of 0.20 m^3/year. The average rainwater retention benefit per tree is 23.66 times greater than that per shrub, which shows that tree species far exceed shrub species in terms of rainwater retention.

Table 3. Analysis of average rainwater retention benefit per plant of common trees and shrubs in Changchun City.

Categories	Rainwater Retention Benefits (m^3/Year)	(RMB/Year)
Trees	95.78	1467.24
Shrubs	2.63	40.34
Per tree	4.79	73.36
Per shrub	0.20	3.10

3.2. Analysis of Carbon Sequestration and Oxygen Release Benefit of Urban Forests

An important function of trees and shrubs is their ability to sequester carbon and release oxygen by directly absorbing CO2 from the air to form wood and foliar biomass [36] and releasing oxygen through photosynthesis (O2). The model analysis showed, under the same conditions, that the total carbon storage of 20 different tree species was 3715.42 kg, equivalent to RMB 4526.19. The carbon sequestration benefits were 633.85 kg/year, creating an economic value of RMB 772.05/year; oxygen release benefits were 485.86 kg/year, and the price of oxygen production according to the Specification for the Assessment of Forest Ecosystem Service Functions (LY/T1721-2008) was RMB 1000/ton, which translated into an economic benefit of 485.86 RMB/year (Table 4). The total carbon storage of shrubs of 13 different shrub species under the same conditions was 151.55 kg, equivalent to RMB 184.66; the total carbon sequestration and oxygen release benefit was 101.09 kg/year, which was converted into an economic value of RMB 80.55/year. The total carbon sequestration benefit was 45.94 kg/year, creating an economic value of 25.40 yuan/year; the oxygen release benefit was 55.15 kg/year, which translated into an economic benefit of RMB 55.15/year (Table 4).

Table 4. Analysis of carbon sequestration and oxygen release benefits of common trees and shrubs in Changchun.

Categories	Carbon Storage		Carbon Sequestration Benefits		Oxygen Release Benefits	
	(kg)	(RMB)	(kg/Year)	(RMB/Year)	(kg/Year)	(RMB/Year)
Trees	3715.42	4526.19	633.85	772.05	485.86	485.86
Shrubs	151.55	184.66	45.94	25.40	55.15	55.15
Per tree	185.77	226.31	31.69	38.60	24.29	24.29
Per shrub	11.66	14.20	3.53	1.95	4.24	4.24

The data analysis showed that the average carbon storage per tree of 20 common tree species in Changchun was 185.77 kg, which was converted into an economic value of RMB 226.31. The average carbon sequestration and oxygen release benefit is 56.00 kg/year, with an economic value of RMB 62.90/year. The average carbon storage per shrub of 13 common shrub species in Changchun was 11.66 kg, which was converted into an economic value of RMB 14.20. The average carbon sequestration and oxygen release benefit was 7.78 kg/year, creating an economic value of RMB 6.20/year. The average carbon storage ratio of common trees to shrubs in Changchun was 16:1; the average annual carbon sequestration and oxygen release benefit ratio was about 10:1. Thus, both the carbon storage and annual carbon sequestration and oxygen release benefits of tree species were much higher than those of shrub species.

3.3. Analysis of the Air Quality Improvement Benefits of Urban Forests

With urbanisation, air pollution is increasing. Air pollution poses a clear hazard to human health, especially to people suffering from respiratory diseases [36,37]. Urban forests can improve air quality by absorbing gaseous pollutants (e.g., CO, O_3, NO_2, SO_2) and intercepting particulate matter (PM 2.5) through the surface of the leaves, and it is an effective way to mitigate air pollution in the long term.

The benefits of trees and shrubs on air quality improvement were measured by quantifying the ability of common tree and shrub species in Changchun to remove CO, O_3, NO_2, SO_2, PM 2.5 and other pollutants using the i-Tree Eco model. The annual air quality improvement benefit of 20 common trees in Changchun was 68,010.51 g/year, which translated into an economic benefit of RMB 89.94/year. The average benefit per tree was 3400.53 g/year. The air quality improvement benefit of 13 common shrubs in Changchun was 362.56 g/year, which translated into an economic benefit of RMB 0.46/year, while the average benefit per tree is 27.89 g/year. Table 5 showed that the ratio of air quality improvement benefits of trees and shrubs was 195.5:1. Although the air quality improvement benefits per tree were relatively low, the air quality improvement capacity of tree species was much higher than that of shrubs.

Table 5. Analysis of air quality improvement benefits of common trees and shrubs in Changchun.

Categories		Trees	Shrubs	Per Tree	Per Shrub
Pollution removal (g/year)	CO	382.72	11.34	19.14	0.87
	O_3	2809.44	76.54	140.47	5.89
	NO_2	2741.40	65.20	137.07	5.02
	SO_2	1635.77	42.52	81.79	3.27
	PM 2.5	60,441.18	166.96	3022.06	12.84
Aggregate		68,010.51	362.56	3400.53	27.89
Value of pollution removal (RMB/year)	CO	0.51	0.01	0.03	0.00
	O_3	3.72	0.1	0.19	0.01
	NO_2	3.58	0.13	0.18	0.01
	SO_2	2.16	0.04	0.11	0.00
	PM 2.5	79.97	0.18	4.00	0.01
Aggregate		89.94	0.46	4.50	0.03

Note: 0 is because the value is too small to be displayed.

3.4. Analysis of the Energy Saving Benefits of Urban Forests

Urban forests can achieve energy savings by cooling and keeping buildings warm. McPherson et al. found that urban trees and other vegetation near buildings can lower indoor air temperatures in summer, reducing indoor temperatures by 3 °C, compared to areas of the same building that are not shaded by vegetation. In winter, urban trees can reduce heating costs by acting as windbreaks, lowering wind speeds and reducing the rate of air infiltration into buildings by 50 percent, saving up to 25 percent of potential heating costs annually [35,38].

The i-Tree Eco model was used to calculate the energy saving benefits of trees by the energy consumed to maintain and reduce the same temperature in the process of insulating the building in winter and cooling the building in summer. According to the calculations of this model (Table 6), the energy saving benefit of 20 common tree species in Changchun was RMB 1657.52/year, and the average energy saving benefit per tree was RMB 82.876/year. Meanwhile, 13 common shrub species in Changchun accelerated the building temperature drop during the winter heating period, with an energy saving benefit of RMB −0.26/year and an average energy saving benefit per shrub of RMB −0.02/year.

Table 6. Analysis of energy savings benefits of common trees and shrubs in Changchun.

Categories	Heating				Cooling		Aggregate
	MBTU/Year	RMB/Year	KWH/Year	RMB/Year	KWH/Year	RMB/Year	RMB/Year
Trees	18.396	1476.36	154.492	98.88	128.548	82.28	1657.52
Shrubs	0	−0.39	−0.039	0	0.338	0.26	−0.26
Per tree	0.9198	73.818	7.7246	4.944	6.4274	4.114	82.876
Per shrub	0	−0.03	−0.003	0	0.026	0.02	−0.02

Note: MBTU is British thermal unit, based on the default price of 80.22 yuan/MBTU. 0 is because the value is too small to display.

3.5. Analysis of the Annual Ecological Benefits of Urban Forests in the Central City of Changchun

According to the linear layout of urban forests, the tree coverage rate was calculated (as in Equation (1)) as 29.81%, indicating that the cost–benefit of urban forest reaches the equilibrium state when the greening rate in residential areas is 35% and the tree coverage rate is 29.81%. Based on the results of the assessment analysis of the i-Tree Eco model (Table 7), the ecological benefits of the 20 common trees were RMB 4472.61/year, with an average ecological benefit of 223.64 yuan/year per tree. The energy saving benefit was the highest at 37.1%, followed by the rainwater retention benefit at 32.8%, the carbon sequestration and oxygen release benefit at 28.1%, and the lowest was the air quality improvement benefit at 2.0%. The ecological benefit of 13 common shrubs was RMB 123.16/year, with an average ecological benefit of RMB 9.47/year per shrub. The carbon sequestration and oxygen release benefit were the most significant at 65.4%, followed by the rainwater retention benefit at 32.8%, the air quality improvement benefit at 2.1%, and the energy savings benefit was negative at −0.3%. The average annual ecological benefit ratio of individual trees to shrubs was 23.6:1.

Table 7. Analysis of annual ecological benefits of common trees and shrubs in Changchun.

Categories	Carbon Sequestration and Oxygen Release Benefits (RMB/Year)	Energy Efficiency Savings (RMB/Year)	Rainwater Retention Benefits (RMB/Year)	Air Quality Improvement Benefits (RMB/Year)	Total Benefits (RMB/Year)
Trees	1257.91	1657.52	1467.24	89.94	4472.61
Shrubs	80.55	−0.26	40.34	2.53	123.16
Per tree	62.90	82.88	73.36	4.50	223.64
Per shrub	6.20	−0.02	3.10	0.19	9.47

According to the results of field research, the ratio of common trees and shrubs in Changchun urban forests was about 1:3. The common planting spacing is 3–8 m for trees and 1–5 m for shrubs [39,40]. The spacing of trees and shrubs in this study was taken as the median, with 5.5 m spacing for trees and 2.5 m for shrubs. An urban forest of 1 ha created ecological benefits of about RMB 51,400/year. Based on the land-cover data of the central urban area, using the Symbology function under the GIS platform and the Calculate Geometry tool to display the land-cover data (Figure 5), the urban forest area of the central urban area of Changchun was calculated to be 96.55 km^2, accounting for 15.84% of the central urban area (as shown in Table 8). It can be determined that the ecological benefit of urban forest in the central city of Changchun was about RMB 496 million/year.

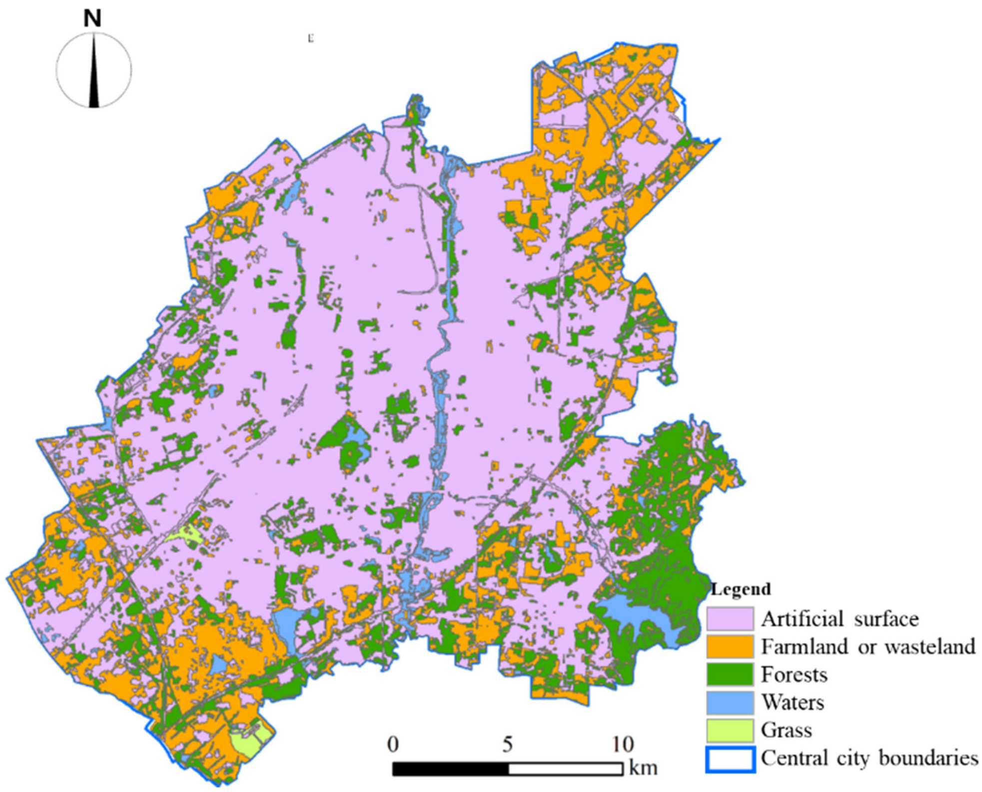

Figure 5. Land Cover Classification Map of Changchun Central City.

Table 8. Land cover classification in the central city of Changchun.

Type of Land Cover	Area (km^2)	Proportion (%)
Artificial surface	381.49	62.6
Agricultural land or wasteland	107.66	17.67
Forests	96.55	15.84
Waters	21.40	3.51
Grass	2.30	0.38
Total area	609.4	100

3.6. Cost–Benefit Analysis of Urban Forests

Referring to the prices posted on a website that provides large-scale supply of plants from all over the country in China (https://www.yuanlin.com/ (15 August 2021), the average economic cost of 20 common trees is about RMB 642/plant, and the average economic cost of 13 common shrubs is about RMB 83/plant. Comparative analysis shows that the ratio of annual benefit to economic cost gradually increases with the proportion of trees, but the growth rate exhibits a gradual decline.

To investigate the economic costs and annual benefits comprehensively, the average economic cost of RMB 66,784.22 and annual ecological benefit of RMB 20,327.3 were used to compare with Table 9. It was found that when the percentage of trees was between 35% to 40%, it is closest to the mean value, so the percentage of trees in the range 35% to 40% is subdivided in the difference of 1% per level (as in Table 9). If the ratio of trees and shrubs is adjusted to 9:16, the annual ecological benefit of an urban forest of 1 ha will be 58,100 yuan/year, and the ecological benefit of urban forests in the central city of Changchun will be about RMB 561 million/year. Urban forests can create an additional benefit of 65 million yuan per year. The comparative analysis of the calculated results shows that the economic costs and annual benefits of urban forest construction is closest to the mean value when the tree proportion is 36%. When the percentage of trees is in the range of 0% to 36%, the annual ecological benefits increase more rapidly than the economic costs of urban forest construction; when the proportion of trees is in the range of 36% to 100%, the annual ecological benefits increase more slowly than the economic costs (Figure 5).

Table 9. Effect of different proportions of trees and shrubs on economic costs and annual ecological benefits.

Trees: Shrubs	Number of Trees (Plants)	Number of Shrubs (Plants)	Cost (RMB)	Annual Benefits (RMB)	Annual Benefits/Costs
0:100	0	560	46,480	5303.2	0.1141
5:95	23	446	52,124.16	9479.60	0.1819
10:90	40	364	56,202.31	12,497.23	0.2224
15:85	53	302	59,286.80	14,779.59	0.2493
20:80	63	253	61,701.36	16,566.24	0.2685
25:75	71	214	63,642.86	18,002.86	0.2829
30:70	78	182	65,237.92	19,183.12	0.2940
35:65	84	155	66,571.67	20,170.03	0.3030
40:60	88	132	67,703.47	21,007.51	0.3103
45:55	92	113	68,675.95	21,727.10	0.3164
50:50	96	96	69,520.55	22,352.05	0.3215
55:45	99	81	70,260.93	22,899.90	0.3259
60:40	102	68	70,915.25	23,384.07	0.3297
65:35	104	56	71,497.71	23,815.06	0.3331
70:30	106	46	72,019.52	24,201.17	0.3360
75:25	108	36	72,489.69	24,549.07	0.3387
80:20	110	28	72,915.52	24,864.17	0.3410
85:15	112	20	73,303.00	25,150.88	0.3431
90:10	113	13	73,657.09	25,412.89	0.3450
95:5	114	6	73,981.93	25,653.25	0.3468
100:0	116	0	74,280.99	25,874.55	0.3483

4. Discussion

4.1. Tree Species Selection in Greenland Construction Based on Ecological Benefit Analysis in Changchun

The comparative analysis of the calculated results shows that the economic costs and annual benefits of urban forest construction is closest to the mean value when the tree proportion is 36%. When the percentage of trees is in the range of 0% to 36%, the annual ecological benefits increase more rapidly than the economic costs of urban forest construction; when the proportion of trees is in the range of 36% to 100%, the annual ecological benefits increase more slowly than the economic costs (Figure 5). From the benefits analysis of rainwater interception, carbon sequestration and oxygen release, air quality improvement, and energy conservation, the ecological benefit of tree species is much higher than that of shrub species. The comparison of the various types of benefits of tree and shrub species showed that the tree species far exceeded the shrub species in both individual and annual benefits. Especially, the shrub species had a negative energy saving benefit for buildings. Therefore, tree species are the main influencing factor of urban forest ecological benefits for Changchun.

Although many scholars have conducted assessments of urban forest ecology in terms of air quality, carbon sequestration and oxygen release, rainwater interception, and energy conservation [9,21,22,27], there is still relatively little research targeted to specific proportion references for urban central urban areas. Therefore, this paper is also an extension of existing research. From the cost–benefit analysis results, selecting the appropriate proportion of tree species can bring maximum benefits. Based on the results of Figure 5, when the planting ratio of trees and shrubs is 1:3, the economic cost for 1 ha of residential area is about RMB 63,642.86, and the annual ecological benefit created is about RMB 18,002.86. Thus, both cost and annual benefit are relatively low. When the ratio of trees and shrubs is adjusted from 1:3 (25:75) to 9:16 (36:64), the economic cost increases by 4.98%, but the annual ecological benefits grow by 13.03%.

4.2. Tree Species Coverage Could Be Considered as One of the Indicators in Residential Area Design

The research results of scholar Tenley M indicate that socioeconomic factors at the community level are usually related to urban vegetation coverage [38], and this study is also an extension of this research. This study not only focuses on vegetation coverage, but also concludes that tree coverage is a key indicator. The results of tree coverage rate fits with the results of Zhang Li's research on the optimisation strategy of green space planning and design in residential areas that trees can provide the optimal cooling effect when the tree coverage reaches 25% to 30% on residential land with relatively good facilities and environments [40–43]. Considering the 1:3 ratio of trees and shrubs required by the Changchun City Bureau of Landscaping, the number of trees in 1 ha of residential area, at the greening rate of 35%, is 71, and the calculated tree coverage is 24.90%; low in both costs and benefits. Therefore, in addition to the current standards of green space ratio and green space per capita for residential construction, another indicator, the tree coverage ratio, should be added.

The linear layout of urban forest is therefore more conducive to energy efficiency due to its wider exposure to constructions. Furthermore, linear urban forests can be laid out along the road, making them more conducive to the absorption of CO, NO_2, and SO_2 pollutants from vehicle exhausts and the removal of respirable particulate pollutants in the air, such as PM2.5 and PM10. The higher the concentration of carbon dioxide, the faster the carbon absorption rate of urban forests, so urban forests arranged on both sides of the road have better carbon sequestration and oxygen release benefits. The comparison shows that the linear layout of urban forest is more ecologically efficient.

4.3. Strategies for Improving the Ecological Benefits of Urban Forests in Changchun

For urban planning and construction, the spatial layout of linear urban forests has the best ecological benefits based on the ecological benefits analysis of urban forests, followed by planar forests (with the same number of trees). According to the document "Overall Urban Design of Changchun City (2017–2035)" released by the Changchun government (http://www.changchun.gov.cn/zjzc/xfzc/201711/t20171127_436505.html (27 November 2017), the construction of green spaces includes green corridor systems and ecological green park systems in the central urban area. To achieve more ecological benefits, we suggest adopting a method that combines linear and planar green spaces to form a flow green corridor system mainly composed of tree species. Specifically, the linear layout refers to the construction of a flow green corridor based on the river system, and the planar layout refers to urban forest patches such as parks.

We suggest that in plant configuration, the proportion of tree species should be more than 36%. At the same time, tree species with high ecological benefits should be planted, including white cuttage, green cuttage, Picea koraiensis, black Chinese pine, poplar, weeping willow, birch, etc. With sufficient funds, the proportion of evergreen trees with high costs and high ecological benefits should be increased, including white cuttage, green cuttage, Picea koraiensis, black Chinese pine, etc. In the absence of sufficient funding, the proportion of deciduous tree species with low costs and relatively high ecological benefits should be increased, including poplar, weeping willow, white birch, etc.

For optimization of street space, the proportion of trees in the street should not be 36%, while in some residential streets, the proportion of trees should be increased accordingly, with trees being the main type. For example, the avenue connecting TOD stations and flowing green spaces improves human thermal comfort through ecological functions such as shading and cooling during hot summers, increasing the likelihood of public travel and recreational activities.

5. Conclusions

This study adopts the quantitative assessment model of urban forest ecological benefits and provides an efficient and convenient research path and tool for the exploration of the ecological benefits, economic benefits, and cost–benefit relationships of urban forests under different regional conditions, thus providing quantitative support for the development of forests and ecological civilisation in the urban area.

We evaluated the ecological benefits of urban forests in the central city of Changchun with the i-Tree Eco model, but it is necessary to apply the data of local tree species, climate, and economic costs to increase the accuracy and relevance of the results. The comparative analysis of the ecological benefits of trees and shrubs in the urban forests indicates that tree species are the main factor affecting the ecological benefits of urban forests.

The cost–benefit analysis of urban forests shows that when the proportion of trees is 0.36, the economic costs and ecological benefits of urban forests reach the mean value, and as the proportion increases, the marginal benefits decrease. When linearly distributed, urban forests show a wider influence and greater ecological benefits. Considering the cost–benefit relationship and the type of spatial layout, the economic costs and ecological benefits of urban forests are balanced at 29.81% tree coverage. The current ecological benefits of urban forests in central Changchun city in terms of carbon sequestration and oxygen release, energy saving, rainwater retention and air quality improvement is worth RMB 496 million/year. If the percentage of trees is adjusted to 0.36, the ecological benefits can be increased by RMB 61 million/year.

In addition, much research has directly calculated ecological benefits through i-Tree Eco models for cold regions. We compared several cities horizontally, such as Hefei (subtropical region) [44] and Shenyang (cold region) [45] but did not find any obvious characteristic conclusions. This is also the limitation of this research; that the calculation is based on limited parameters. We will continue the research comparing our results with the relevant ones horizontally in the following research, to identify key factors and indicators for improving the ecological benefits of urban forests under different climate conditions.

Author Contributions: Conceptualisation, H.Z. and D.Z.; methodology, D.Z. and X.J.; software, D.Z.; validation, D.Z., X.J. and H.Z.; formal analysis, D.Z.; investigation, D.Z. and H.Z.; resources, D.Z. and X.J.; data curation, D.Z.; writing—original draft preparation, D.Z. and H.Z.; writing—review and editing, X.J. and Z.L., H.Z. and S.Z.; visualisation, D.Z. and Z.L.; supervision, H.Z.; project administration, H.Z. and X.J.; funding acquisition, H.Z. and X.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (grant number 52178042), Key projects of Jilin Provincial Department of Science and Technology (grant number 20210203213SF), The 13th Five-Year Plan for Education Science in Jilin Province (grant number GH20122), and the Technology Research Project of Jilin Provincial Department of Education in China (grant number JJKH20220299KJ).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Common tree species and shrub species in Changchun urban forest.

Categories	Scientific Name
Trees	*Acer triflorum*
	Betula pendula subsp. *mandshurica*
	Catalpa ovata
	Crataegus pinnatifida
	Juglans mandshurica
	Picea koraiensis
	Picea meyeri
	Picea wilsonii
	Pinus tabuliformis var. *mukdensis*
	Populus alba
	Prunus davidiana
	Prunus padus
	Prunus persica
	Prunus salicina
	Prunus sibirica
	Quercus mongolica
	Salix babylonica
	Salix babylonica
	Syringa reticulata
	Ulmus alata
Shrubs	*Acer tataricum* subsp. *Ginnala*
	Cornus alba
	Forsythia suspens
	Hydrangea paniculata
	Ligustrum obtusifolium
	Ligustrum quihoui
	Prunus tomentosa
	Prunus triloba
	Sorbaria sorbifolia
	Spiraea japonica
	Spiraea thunbergii
	Syringa oblata
	Weigela florida

Table A2. The unit price for seedlings of 20 common trees in Changchun.

Number	Arbor Species	Diameter at Breast Height (cm)	Unit Price (RMB)
1	*Acer triflorum*	10	640
2	*Betula pendula* subsp. *mandshurica*	10	120
3	*Catalpa ovata*	10	200
4	*Crataegus pinnatifida*	10	200
5	*Juglans mandshurica*	10	300
6	*Picea koraiensis*	10	500
7	*Picea meyeri*	10	3500
8	*Picea wilsonii*	10	3500
9	*Pinus tabuliformis* var. *mukdensis*	10	400
10	*Populus alba*	10	100
11	*Prunus davidiana*	10	220
12	*Prunus padus*	10	550
13	*Prunus persica*	10	270
14	*Prunus salicina*	10	300
15	*Prunus sibirica*	10	400
16	*Quercus mongolica*	10	600
17	*Salix babylonica*	10	140
18	*Salix babylonica*	10	140
19	*Syringa reticulata*	10	550
20	*Ulmus alata*	10	200
	Average price		642

Table A3. The unit price of seedlings of 13 common shrubs in Changchun.

Number	Shrub Species	Total Tree Height (cm)	Unit Price (RMB)
1	*Acer tataricum* subsp. *Ginnala*	150	65
2	*Cornus alba*	150	20
3	*Forsythia suspens*	150	20
4	*Hydrangea paniculata*	150	100
5	*Ligustrum obtusifolium*	150	50
6	*Ligustrum quihoui*	150	90
7	*Prunus tomentosa*	150	65
8	*Prunus triloba*	150	65
9	*Sorbaria sorbifolia*	150	60
10	*Spiraea japonica*	150	215
11	*Spiraea thunbergii*	150	215
12	*Syringa oblata*	150	35
13	*Weigela florida*	150	20
	Average price		83

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