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Urban Forest Ecosystem Services Vary with Land Use and Species: A Case Study of Kyoto City

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Abstract: The demand for urban ecosystem services increases with the rapid growth of the urban population. The urban forest is a crucial ecosystem services provider in cities. To achieve a better estimation of urban ecosystem services, an understanding of the link between heterogeneity and ecosystem services within cities is needed. Other than street trees and forest remnants, the contribution of dispersed green spaces should also be considered. In this study, a ground-based sample quadrat investigation of trees across a sequence of land types in Kyoto City was applied. The ecosystem services and monetary values of trees were further calculated using a customized i-Tree Eco tool. The ecosystem services calculated include carbon storage and sequestration, air pollutants removal, and runoff reduction. Ecosystem services of different land use classes were compared at both quadrat and single-tree levels. We found no significant difference across land use for all the ecosystem services at the quadrat level. However, ecosystem services were different across land use at the single-tree level. We performed a species-specific analysis and found that the pattern of ecosystem services at the single-tree level across land use varies with both the service tested and species. Our study suggests that the heterogeneity within a city should be considered when estimating urban ecosystem services. The results also provide insight into the urban green space management of Kyoto City.

Keywords: ecosystem services; land use; i-Tree; green infrastructure; urban

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1. Introduction

The world's urban population is expected to increase from 55% in 2019 [1] to 68% by 2050 [2], thus growth of demand for ecosystem services in cities would ensue. The relation between demand and supply of ecosystem services varies with scale. Locally generated ecosystem services are more closely related to the living quality of the resident, and some of them are irreplaceable by other distant sources of ecosystem services (for example, mitigation of heat island effect) [3]. Considering the numerous population size in cities, the social and economic value of ecosystem services within cities can be surprisingly high [4]. Besides, a global assessment highlighted how massive urbanization is impacting biodiversity and ecosystems around the world negatively [5]. Therefore, an improvement of urban ecosystem services could potentially benefit city residents and mitigate the loss of ecosystem services globally.

Yet despite the importance of urban ecosystem services evaluation [3], most of the studies and the implementation of the research findings into land use policy, are in North America, Europe, and China [6,7] (case studies see New York City [8] and Berlin [9]). Besides, even though related evaluation tools like i-Tree have been widely applied in many cities around the world, urban ecosystem services research in Japan has been less addressed. A pilot study evaluated the ecosystem services of street trees in Kawasaki City in Japan using i-Tree [10]. Other than that, only some case studies using a similar approach were found [11–13].

Ecosystem services are estimated with a variety of methods, including indicators and valuation. Indicators are used to quantify the state and change of the objects of interest. Some of the commonly used indicators are crop yield for food production, carbon storage and carbon sequestration for climate change mitigation, and runoff reduction for hydrological regulation. Regarding the valuation, two methods are applied to estimate ecosystem services' monetary value. One is the traditional economic method using firsthand data, including the stated preference method and revealed preference method. Though the empirical, field-based method can provide more accurate results [14], it is time-consuming and limited on the scale. Therefore, the other method, value transfer (or 'benefit transfer') is widely used in ecosystem evaluation [15], for which the monetary value estimation of one location (the 'reference ecosystem') is transferred to another (the 'target location') [16]. The value transfer method is frequently applied in regional services estimation based on the area of land use/land cover types and per unit area ecosystem service value of each type. In these studies, cities are categorized as 'urban area' or 'built-up area,' and the ecosystem service of the category is estimated with a constant per unit area ecosystem service value. Particularly, the per unit area ecosystem service value for urban ecosystem from Costanza et al. [17] has been widely applied (e.g. see [18,19]). Some other research modified the per unit area ecosystem service value based on the local context like scarcity value effect [20]. However, the land use/land cover-based value transfer method could cause uncertainty in urban ecosystem service estimation since it ignores the high heterogeneity in cities and rapid change of land use/land cover [6,15]. To get a more specific per unit area ecosystem service value for urban ecosystems, within-city research and inter-city comparison research is needed.

Among the service providers in urban ecosystems (e.g., forest patches, waterways and lakes, parks, brownfields, urban agriculture [6,21,22]), the urban forest is one of the foremost. As a crucial local ecosystem services provider in cities, urban forest functions in many services like carbon storage and sequestration, noise reduction, air quality improvement, energy conservation, and recreation [3,23]. While the ecosystem services of urban forests might have been underestimated since many previous studies focused on remnant forests or street trees (e.g., [24,25]), partially due to data availability. However, the dispersed green spaces such as private gardens have been less studied, despite the fact that their importance to urban ecosystem services has been proved [21,22,26].

To estimate the ecosystem services of urban forests more precisely, i-Tree Eco has been applied worldwide in more than one hundred countries. Developed by the United States Department of Agriculture, i-Tree Eco allows users to calculate several ecosystem services (carbon storage and sequestration, pollutants removal, runoff reduction, etc.) of each tree with field investigation data of tree species, size, and condition. Though i-Tree Eco enhances users to manage urban forest more accurately, even at a single-tree level, most research only presented the results of inferred total ecosystem services of the whole research area (e.g., see [27]) or results by species [28,29]. One possible reason is being guided by the automatically generated report of the tool. These results, however, provide little information on the link between within-city heterogeneity and urban ecosystem services. Only a few research reported ecosystem services across land use/land cover within cities [21,30].

To address the gaps mentioned above, we conducted an urban ecosystem services evaluation at a Japanese city, Kyoto. The study is partially aimed at enriching the database of urban ecosystem services with detailed ground-based investigation data and the i-Tree Eco tool. Another main objective of this article is to link urban heterogeneity and urban ecosystem services by comparing ecosystem services across land use. We expected that ecosystem services would differ across land use types.

In this study, a pre-stratified sampling method based on the area of land use classes was applied for field data collection, then the i-Tree Eco tool was used to calculate the urban forest structure, tree compensatory value, and ecosystem services. The ecosystem services, including carbon storage and sequestration, air pollutants removal, and runoff reduction, were estimated for the entire study area and allocated to each tree, then further grouped by quadrat. We compared ecosystem services at both quadrat level and single-tree level across land use classes. For a better understanding of the link between heterogeneity and ecosystem services, we also compared the results of Kyoto City with the studies of other cities.

2. Materials and Methods

2.1. Study Area

Kyoto City (35°19′16″ N–34°52′30″ N, 135°33′33″ E–135°52′43″ E), the capital of Kyoto Prefecture, is located in Kyoto Basin of Kansai region, Honshu Island, Japan, with an area of 828 square kilometers. The city is dominated by a humid subtropical climate with hot, humid summers, and cold, dry winters. It is one of the 'Cities designated by government ordinance of Japan' with a population of 1.47 million (0.73 million households) in 2019. The area of the built-up area of the city is 144 square kilometers.

As a planned capital, Kyoto city was founded when Emperor Kammu relocated the capital in 794. The Japanese borrowed the basic city layout from Chang'an, China in the Tang-dynasty, part of which is a grid spatial system dividing the city into blocks. The land use pattern of the city, however, mainly formed in modern times. During the infrastructure promotion at the end of the Meiji era (1868–1912), the city center was constructed based on the traditional commercial area. The administration boundary expanded significantly in the Taisho era (1912–1926), and an expansion and construction of the industrial area and residential area was achieved based on the urban planning laws [31]. Kyoto city is now, overall, a mono-centric city. The city center is mainly used as a commercial area. The industrial area is mostly located in the west and south of the city. The residential area is in the surrounding area (Figure 1).

2.2. Tree Data Collection

According to the urban planning system and City Planning Law of Japan, urban land use is categorized into 12 classes, with a regulation on the architectural form and use of the buildings constructed [32]. We aggregated them into 6 classes from city fringe to city center (Table 1): ResLow (Low-rise residential zone), ResHigh (mid/high-rise residential zone), ReSOther (Other residential zone), Ind (Industrial zone), ComNbr (Neighborhood commercial zone), Com (Commercial zone). For field investigation, 200 quadrats (20 m × 20 m) were established, including the alternative ones, by stratified sampling method based on the area of the land use classes [33]. The field investigation was conducted between May and August in 2019. The number of the quadrats accessed and investigated (n = 175 [34]) for each land use class is shown in Figure 1.

Following the i-Tree Eco workbook [33], the information of the quadrats and trees was collected. For each quadrat, we took photos of the surrounding environment and the vegetation. Information of each tree (woody plants higher than 2 meters) in a quadrat, including species, height, diameter at breast height (DBH), canopy missing percentage, crown size, crown health condition, and crown light exposure, were collected. A total of 1240 trees (of 118 species) was recorded in 151 out of the 175 quadrants (Table 1).

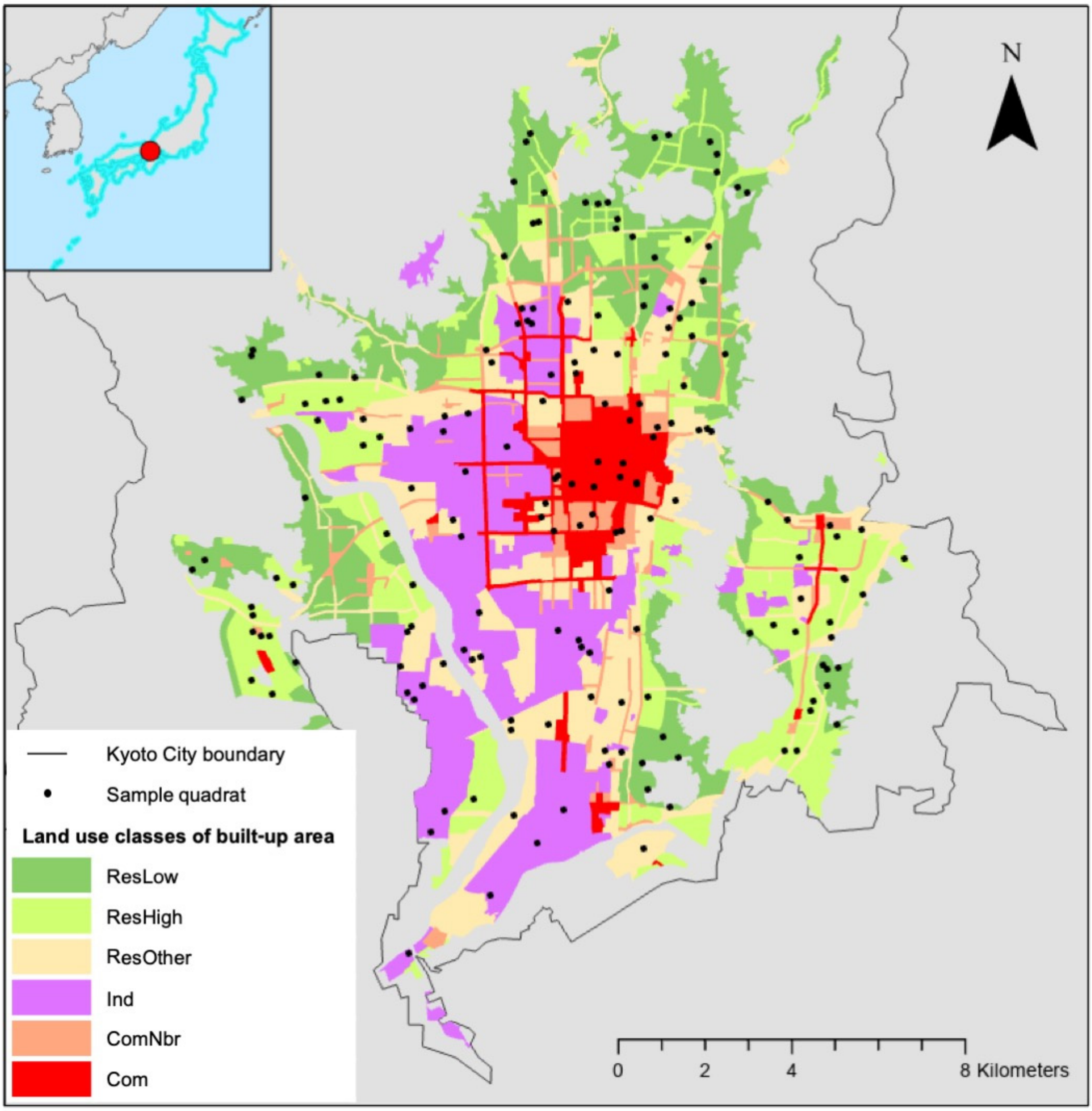

Figure 1. Land use of Kyoto City and distribution of quadrats (mapping under WGS 1984).

Table 1. Sample quadrats by stratified sampling method in this research.

Land Use Class	Area (ha)	Proportion of Area	Number of Quadrats	Number of Trees
ResLow	3519	24%	35	399
ResHigh	3027	21%	38	368
ResOther	3113	21%	34	218
Ind	3213	22%	23	134
ComNbr	864	5%	9	77
Com	1009	7%	12	44

2.3. Evaluation of Ecosystem Services and Monetary Value

i-Tree model has been widely used to help managers and researchers to quantify urban forest structure, ecosystem services, and tree monetary value. We calculated three values of each tree: compensatory value, representing compensation for the loss of a tree [35,36]; monetary value of carbon storage, representing the cumulative result of net carbon sequestration for years; annual ecosystem services, including carbon sequestration, air pollutants removal, and runoff reduction. Though cultural service is one of the most critical components of ecosystem services in cities, i-Tree is not capable of calculating it for now. We will briefly introduce the method for structure and ecosystem services evaluation, and valuation of tree monetary value in the following sections; for more details refer to i-Tree method documentation [37]. To improve the accuracy of results, a modified i-Tree model with local parameters of Kyoto City was applied (see Table S1 for model details and parameters list).

2.3.1. Structure

Leaf area is estimated based on species, total height, crown base height, crown width, and percent crown missing. The method is a species-specific regression equation with a shading coefficient (percent light intensity intercepted by foliated tree crowns) for deciduous urban species, while a shading coefficient of 0.91 is applied for conifer trees [38]. Leaf area index (LAI) is calculated with leaf area and adjusted with the overlap of tree crowns or light exposure. Leaf biomass is calculated based on leaf area with species-specific convert factor. Total biomass for each tree is calculated using species-specific allometric equations from the literature with DBH and total height (see [39,40] for the attributes and references of the equations).

2.3.2. Carbon Storage and Carbon Sequestration

Carbon storage is estimated based on biomass and carbon content. For evergreen and palm species, leaf biomass is added. Carbon sequestration is estimated based on the growth rate. The growth rates are estimated with the measurement of radial growth increments [40], length of the growing season, and the growth adjustment factor of crown health and crown light exposure [38]. For valuation of the ecosystem services, the social cost for carbon in Japan (10,600 Yen, which is about 96 US dollars per ton carbon) from the Japanese government document [41] was applied.

2.3.3. Air pollutants Removal and Health Benefits

Air pollution removal is estimated using the percent tree cover and leaf area index. The pollutants estimated include nitrogen dioxide (NO_2), ozone (O_3), particulate matter less than 2.5 µm ($PM_{2.5}$), and sulfur dioxide (SO_2). In the locations supported more sufficiently in i-Tree Eco (e.g., cities in the US and Canada), the tree data is merged with local pre-processed weather and air pollution concentration data for the evaluation of pollutants removal. However, in this case, since Kyoto City is not officially supported by default, we input the local weather data from local monitor stations manually. The value of air pollutant removal is assessed by the BenMAP method [42] that estimates avoided costs for adverse health incidences based on the air quality improvement and medical records across the US.

2.3.4. Runoff Reduction

Runoff reduction in i-Tree Eco is estimated based on the difference between the runoff with current tree cover and that without trees [40]. In the simulation, rainfall interception of trees and runoff are calculated mainly by precipitation, leaf area index, and infiltration with a time step of an hour [43]. One limitation of the model is that the water reaching the pervious surface is assumed to be absorbed by the soil, while the water reaching the impervious surface is assumed to become urban surface runoff. Besides, though the impervious cover rate is estimated by JAXA satellite imagery, the number is assumed to be constant across the research area. To reflect the local economic benefit of the ecosystem service, we used the stormwater control facilities cost estimation of Suita City of Japan (719 yen per m^3, which is about 7 US dollars per m^3) [13] for the valuation.

2.3.5. Compensatory Value

The compensatory value of trees is estimated using the guideline of the Council of Tree and Landscape Appraisers [36] in i-Tree Eco [37]. The compensatory value of a tree is determined by replacement cost, DBH, and a location-specific per unit trunk area cost. For palm trees, the cost to clear trunk is also considered. The values of these parameters have been compiled for numerous states in the US; while for other countries, an average value of replacement cost and per unit trunk area cost is applied.

2.4. Data Analysis

The collected and calculated data for every single tree was then added to get a quadrat dataset, including average DBH, average LAI, the total number of trees, and the total ecosystem services of each quadrat. Since the assumption of normality for the metrics is violated in this case, the non-parametric statistic method, Kruskal–Wallis rank-sum test, was used to analyze the difference of DBH, LAI, the number of trees, and each ecosystem service among land use classes. For the statistical group comparison where a significant difference was detected, Dunn's test was then applied for a post hoc pairwise comparison. Similarly, at the single-tree level, Kruskal–Wallis rank sum test and Dunn's test were used to test the differences of DBH, LAI, and each ecosystem service across land use classes respectively.

Furthermore, a species-specific analysis was used to compare the single-tree ecosystem services across land use classes by species. To achieve a robust result, only widespread species presenting across a sequence of land use classes with at least 3 individuals for each land use class were analyzed. The target species include *Acer palmatum* Thunb., *Ginkgo biloba* L., 1771, *Ligustrum lucidum* Ait., *Nandina domestica* Thunb., *Osmanthus fragrans* Lour., *Podocarpus macrophyllus* (Thunb.) Sweet, 1818, *Prunus* x *blireana*, *Quercus* x *alvordiana*, and *Zelkova serrata* (Thunb.) Makino.

All the analysis was conducted in R (version 4.0.3), and the difference was considered significant at $p < 0.05$. The *kruskal.test* function was applied for Kruskal–Wallis rank sum test and *dumn.test* function from *dumn.test* package was used for the post hoc comparison.

3. Results

3.1. DBH and LAI

DBH is related to both age and species of trees. Trees with DBH $\leq$ 15 cm accounted for a large proportion across the land use classes (Figure 2). Ind zone had more trees with DBH > 15 cm than others, probably reflecting the low manage intensity of the Ind zone and being constrained by both planting goals and limited space. ComNbr zone was characterized by a larger proportion of trees with DBH $\leq$ 15 cm than the others.

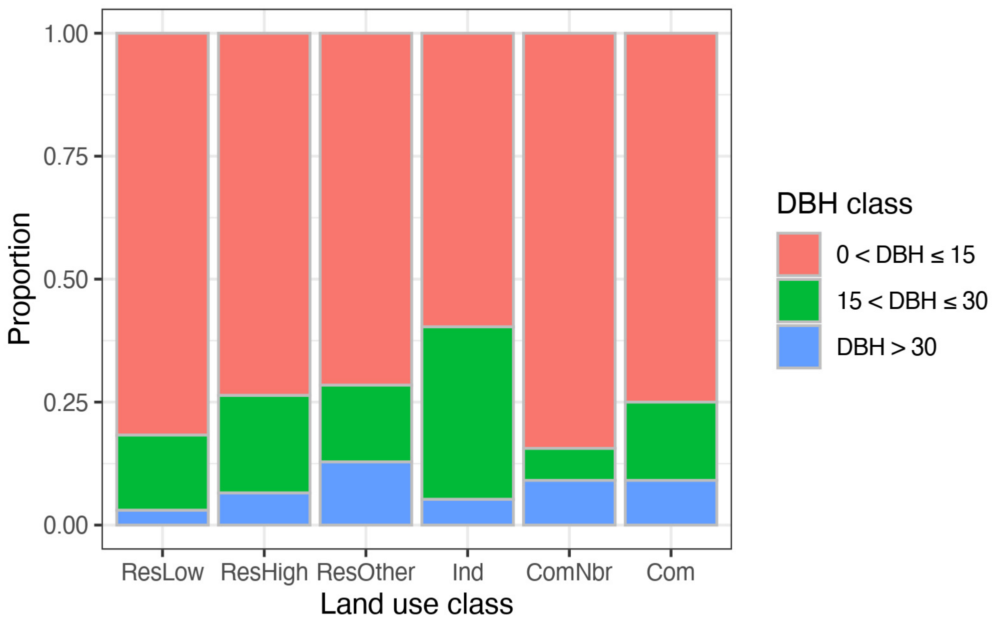

Figure 2. DBH (diameter at breast height) distribution across land use classes.

The LAI for most trees was under 6 (Figure 3). The proportion of LAI < 3 is higher in ComNbr zone, followed by Ind and Com, and residential areas. Among the residential areas, ResLow and ResHigh were characterized by a lower proportion of LAI < 3 and a higher proportion of LAI > 6, which might result from the maintenance of the house owners.

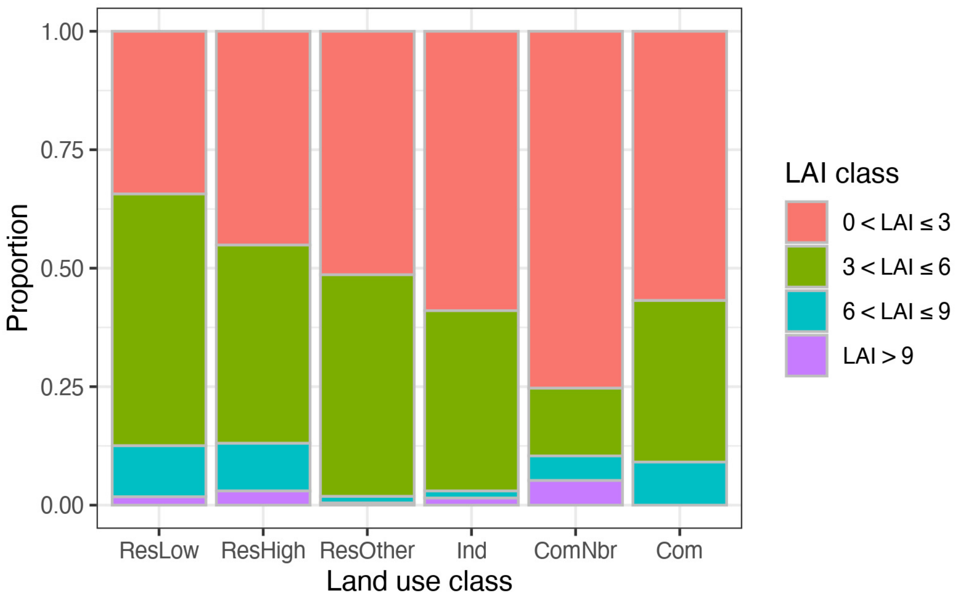

Figure 3. LAI (leave area index) distribution across land use classes.

3.2. Total Monetary Value of Trees

The sum, average number, and median of quadrat annual ecosystem service values, carbon storage value, and compensatory value were calculated (Table 2). The average annual ecosystem service value is 30% as much as the average carbon storage value, while the compensatory value of trees is 121 times of annual ecosystem services. Due to the data distribution, the differences became smaller if compared by median values. The annual ecosystem service value median is 63% of the carbon storage value median, though the compensatory value is still 110 times of annual ecosystem service value median.

Table 2. Valuation of ecosystem services and compensatory value (unit: US dollars).

Item	Sum	Quadrat Average	Quadrat Median
Annual ecosystem services	4285	28	10
Carbon storage	14,339	95	16
Compensatory value	518,712	3435	1128

Regarding the composition of quadrat annual ecosystem service values (Figure 4), $PM_{2.5}$ removal value accounted for about half of the total value, followed by O_3 removal, carbon sequestration, and runoff reduction value. NO_2 removal and SO_2 removal values only account for a small fraction of the total annual ecosystem service value.

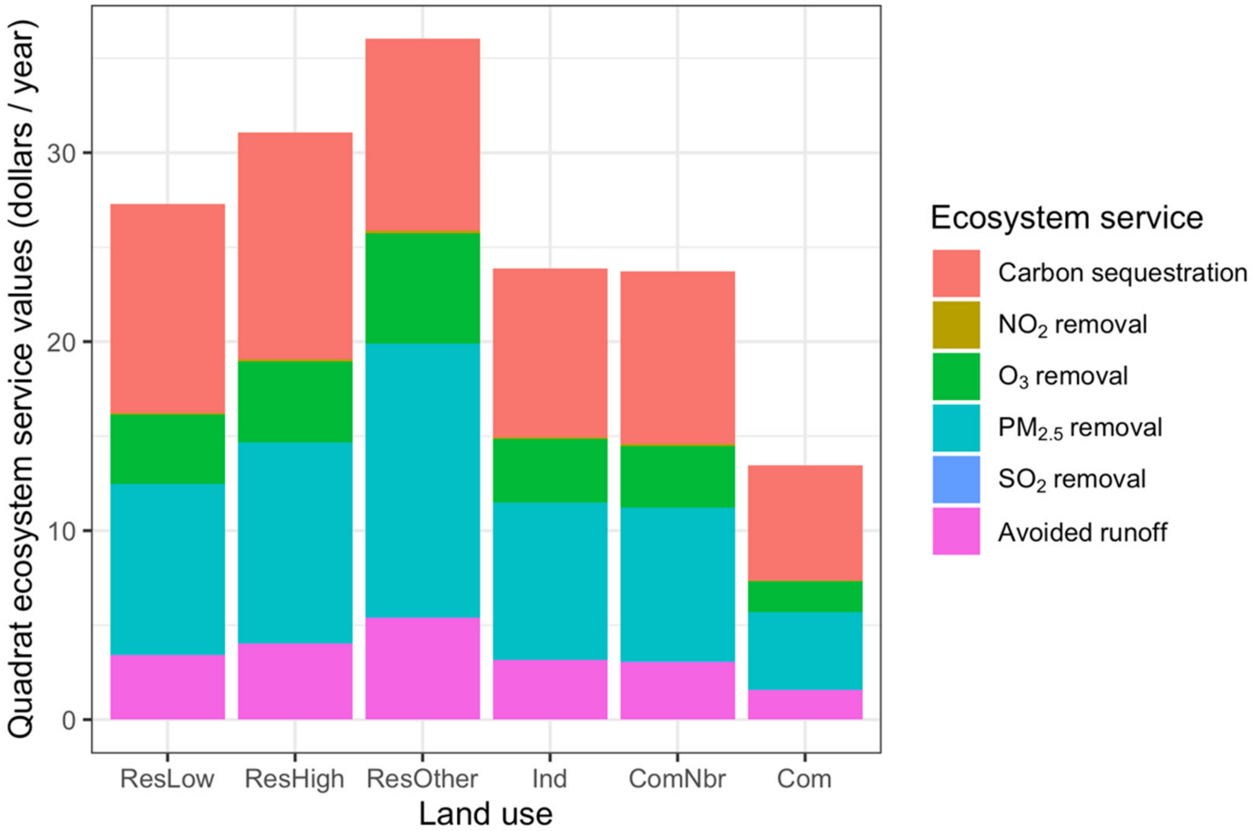

Figure 4. Average valuation of quadrat annual ecosystem services across land use classes.

But it should be noted that, though ecosystem services valuation is convenient for inter-ecosystem-services comparison, the monetary value varies with valuation method covering different aspects of total economic value; and it varies by local context like market value of the services. For example, in this case, the social cost for carbon in Japan is 10,600 Yen (about 96 US dollars) per ton [41], while the monetary value for carbon is 188 US dollars per ton carbon for the US [44]; the stormwater control facilities cost of Suita City, Japan is 719 yen (about 7 US dollars) per m^3 [13], while that estimation in the US is 2.36 US dollars per m^3. The comparison of monetary value between ecosystem services should thus be cautious. Researchers should pay attention to indicators of ecosystem services as well, rather than focusing on valuation only.

3.3. Quadrat Ecosystem Services across Land Use

No significant difference was found for quadrat ecosystem services across land use classes (Table 3). The average and median values of ecosystem services of each land use see Tables S2 and S3.

Table 3. Chi-square statistics of comparison of ecosystem services across land use by Kruskal–Wallis rank sum test (the level of significance is denoted by asterisks: ***, $p < 0.001$).

Scale	Carbon Sequestration	NO_2 Removal	O_3 Removal	$PM_{2.5}$ Removal	SO_2 Removal	Runoff Reduction
Quadrat level	7.68	9.53	9.04	8.00	9.34	7.97
Single-tree level	24.42 ***	55.68 ***	53.94 ***	51.98 ***	54.21 ***	51.68 ***

3.4. Single-Tree Ecosystem Services across Land Use

Different from quadrat ecosystem services, the differences for all ecosystem services at the single-tree level across land use classes (Table 3) were significant. Post hoc comparison indicates that the single-tree carbon sequestration in Com zone and Ind zone were higher than that in the ResLow zone, and the carbon sequestration in the Ind zone is higher than that in the ComNbr zone. Trees in the ComNbr zone had significantly lower air pollutants removal and runoff reduction than the other. The average and median values of ecosystem services of each land use see Tables S2 and S3.

3.5. Species-Specific Analysis

The results of the species-specific comparison (Table 4) indicate that ecosystem services across land use classes were significantly different for most of the species, but not for all the species. *Osmanthus fragrans* and *Podocarpus macrophyllus* showed no difference for carbon sequestration; *Acer palmatum*, *Prunus* x *blireana*, and *Zelkova serrata* showed no difference in all of the ecosystem services across land use classes. A further post hoc pair-wise comparison suggested that the land use class with higher ecosystem services varied with species. For example, *Ginkgo biloba* showed higher ecosystem services in ComNbr; while *Ligustrum lucidum* showed higher ecosystem services in the Ind zone; *Osmanthus fragrans* showed higher ecosystem services in ResOther.

Table 4. Chi-square statistics of species-specific comparison of ecosystem services across land use classes by Kruskal–Wallis rank sum test (the level of significance is denoted by asterisks: no asterisk, $p \geq 0.05$; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$).

Species	Distribution (>3 Individuals per Land Use Class)	Carbon Sequestration	NO_2 Removal	O_3 Removal	$PM_{2.5}$ Removal	SO_2 Removal	Runoff Reduction
Acer palmatum Thunb.	Ind, ResOther, ResHigh, ResLow	4.80	6.12	6.12	6.12	6.12	6.12
Ginkgo biloba L., 1771	Com, ComNbr, Ind, ResHigh	9.86 *	8.04 *	8.04 *	8.04 *	8.04 *	8.04 *
Ligustrum lucidum Ait.	Ind, ResOther, ResHigh, ResLow	18.14 ***	23.75 ***	23.75 ***	23.75 ***	23.75 ***	23.75 ***
Nandina domestica Thunb.	ComNbr, Ind, ResOther, ResHigh, ResLow	14.38 **	23.92 ***	23.92 ***	23.92 ***	23.92 ***	23.92 ***
Osmanthus fragrans Lour.	Ind, ResOther, ResHigh, ResLow	7.51	12.01 **	12.01 **	12.01 **	12.01 **	12.01 **
Podocarpus macrophyllus (Thunb.) Sweet, 1818	Com, ResOther, ResHigh, ResLow	7.51	10.89 *	10.89 *	10.89 *	10.89 *	10.89 *
Prunus x blireana	Com, Ind, ResOther, ResHigh, ResLow	0.78	3.49	3.49	3.49	3.49	3.49
Quercus x alvordiana	Com, ComNbr, Ind, ResOther, ResHigh, ResLow	54.36 ***	72.05 ***	72.05 ***	72.05 ***	72.05 ***	72.05 ***
Zelkova serrata (Thunb.) Makino	Com, Ind, ResOther, ResHigh, ResLow	7.19	5.53	5.53	5.53	5.53	5.53

4. Discussion

4.1. Ecosystem Services across Land Use

Though not statistically significant, among the 6 land use classes in this research, residential zones have higher average and median quadrat carbon sequestration than the others (Tables S2 and S3). A similar result was found in Roanoke of Virginia that per hectare carbon storage and annual carbon sequestration in the residential area is higher than that in the commercial area [21]. A potential reason is that the quadrats of residential zones tend to have more trees or higher LAI than the other land use classes do. On the other hand, surprisingly, at the single-tree level, Com and Ind zones have higher average carbon sequestration than ResHigh and ResLow zones, which is opposite to that at the quadrat level. In this study, we found a significantly higher DBH, LAI, and the number of trees at the quadrat level in residential zones than Com zone and Ind zone overall. Whereas, at the single-tree level, DBH is higher than in Com and Ind zones than ResLow zone (Table S4).

Different from carbon sequestration, air pollutants removal and runoff reduction represent more local ecosystem services. At the quadrat level, though not statistically significant, the average and median value of air pollutants removal are higher in residential zones, followed by Ind or ComNbr, and the minimum value is in the Com zone (Tables S2 and S3). However, due to a higher pollutants emission in the Com zone and Ind zone, those results might suggest a mismatch of ecosystem services supply and demand. An improvement of air pollutants removal services in commercial and industrial areas can potentially benefit public health. Yet, it should also be noted that since the air pollutants data collected by the monitors distributed in the city was aggregated for the simulation, which leads to uncertainties of the results. The air pollutants removal services in commercial zones and Ind zone might be thus underestimated.

The species-specific analysis results suggest that the solution to promote urban ecosystem services should be species-specific rather than one-size-fits-all. For instance, as ubiquitous species, *Ligustrum lucidum* might be less managed thus have higher ecosystem services in the Ind zone; in contrast, it has lower ecosystem services in the ResLow zone possibly due to intense pruning considering residents' aesthetics. A further species-specific study of the underlying causal relationship will enhance a more targeted urban plant management.

A limitation of the comparison should be addressed in which the concept of land use could vary among the research. Land use represents the actual practice and intended use of economic and cultural activities of a certain place, which is driven by both biophysical and socio-economic factors [45]. Land use classification systems are distinguished regarding the scale and purpose of their development [46]. In our study, 'land use' is a classification under the City Planning Law of Japan that describes the potential use and limitation of building types of an area of land; while some other classification systems may emphasize more on actual use of the land.

4.2. Impact of Scale

An implicit assumption is that ecological processes remain consistent across different extents and grain [47], while the convenient assumption usually fails because of the complexity of ecological systems, especially under the high heterogeneity of urban context [48].

Ecological patterns vary across the scale, so is the urban ecosystem service pattern [47,48]. Grain is one component of the scale concept [49]. Quadrat and single-tree levels represent two different levels of grain in our study. No significant difference was found among quadrat ecosystem services across land use classes, while variances were detected at the single-tree level for all ecosystem services (Table 3). These results support the theoretical conclusion that variance between sample quadrats generally decreases with the increasing of grain [50]. The results probably indicate that the variance of ecosystem services at the single-tree scale is "averaged" at the quadrat scale. Compared to the single-tree level, the ecosystem services at the quadrat level are affected by more factors including species, size, and the number of trees, which are further determined by the characteristics related to land use types such as available space and management intensity.

4.3. Comparison of Ecosystem Services between Cities

To compare our results with other studies, the mean value of carbon storage, carbon sequestration, and runoff reduction by land use classes on a per hectare-of-land basis were calculated (Table 5). Both carbon storage (11.51–17.41 ton carbon per hectare) and annual carbon sequestration (1.35–1.60 ton carbon per hectare) of residential zones in this study are lower than that in Roanoke, Virginia, the U.S. (37°16′ N 79°56′ W; 37.00 and 2.28-ton carbon per hectare), while those ecosystem services efficiency of the industrial zone of our study (9.95 and 1.19-ton carbon per hectare) is higher than that of Roanoke (7.31 and 0.48-ton carbon per hectare) [21]. Besides, annual carbon sequestration of residential zones is higher in our research than that of a study for Barcelona, Spain (41°23′ N 2°11′ E; 0.35 and 1.33-ton carbon per hectare for high-density and low-density residential areas) [30]. The runoff reduction ranges from 16.71 to 56.88 m^3/year/ha, which is similar to a study in green spaces of Luohe, China (33°34′ N 114°00′ E; 24.5–51.1 m^3/year/ha) [51].

Table 5. Ecosystem services efficiency in Kyoto City.

Land Use	Carbon Storage (ton/ha)	Carbon Sequestration (ton/ha/Year)	Runoff Reduction (m^3/ha/Year)
ResLow	11.51	1.47	36.08
ResHigh	12.82	1.60	42.48
ResOther	17.41	1.35	56.88
Ind	9.95	1.19	33.35
ComNbr	12.45	1.21	32.38
Com	6.99	0.81	16.71

To compare the results of air pollutants removal with other research, we converted our results into grams per year per square meter tree cover (Table 6). The results in Kyoto City is comparable to those of a study in Strasbourg city, France (NO_2: 0.92 g/year/m^2, O_3: 3.73 g/year/m^2, PM_2: 0.30 g/year/m^2) except for the result of SO_2 removal (0.07 g/year/m^2) [52].

Table 6. Average air purification efficiency of Kyoto City g/year/m^2.

Land Use	NO_2 Removal	O_3 Removal	$PM_{2.5}$ Removal	SO_2 Removal
ResLow	1.01	3.21	0.21	0.42
ResHigh	1.10	3.53	0.23	0.47
ResOther	1.00	3.16	0.20	0.42
Ind	1.04	3.36	0.22	0.44
ComNbr	1.07	3.46	0.23	0.45
Com	0.71	2.35	0.16	0.31

It should be noted that the raw data distribution and sampling method may differ among these studies thus confounding the comparison of the results. For instance, the research in Luohe, China focuses on green space rather than random sample quadrats over the city [51]; and though also presents the results of quadrat ecosystem services in different land use, the study in Roanoke, Virginia mainly focuses on urban vacant [21]. Furthermore, the quadrats with no woody plant are usually excluded for analysis, which also brings bias to the comparison of the results. The workbook of i-Tree Eco [35] has provided a solid base for standard workflow in field investigation, but the difference mentioned above still highlights the barrier in multi-city research. Besides, the results of air pollutants removal are strongly affected by local air quality. Under the same condition, air pollutants removal is higher in the area with higher air pollutants concentrations.

4.4. Ecosystem Service Evaluation in Cities

In the prevalent land use/land cover-based methodology of ecosystem service evaluation, the per-unit value of the urban area is usually considered constant (e.g., see [18,19]).

Though no significant difference was detected for quadrat ecosystem services across land use classes in our research, it could be a result of the high heterogeneity of urban ecosystems rather than homogeneity. Land use is a rough classification under the context of law and policy in Japan. Within a certain land use type, there can be several onsite land cover classes, and quadrat ecosystem services of certain land use classes could be 'averaged' by this mixture. The relationship between land use or land cover and ecosystem services requires further research based on high-resolution geographic data and sampling at a different scale.

Another reason for further enrichment of the urban ecosystem services benchmark database is the heterogeneity between cities. As the comparison of our results with other studies in the previous section shows, per unit ecosystem services could vary across different cities. This comparison indicates that the local context must be considered when evaluating urban ecosystem services.

5. Conclusions

The main purpose of this study is to demonstrate the link between heterogeneity of a city and urban ecosystem services, and the potential contribution of dispersed green to urban ecosystem services. This study captured the structure, ecosystem services, and monetary values of the urban forest in Kyoto City. For urban forest structure analysis, the Ind zone has more mature trees with higher DBH than the other land use; residential zones have a higher proportion of trees with larger LAI. The comparison across land use classes shows that ecosystem services are different across land use at the single-tree level, though no significant difference was detected at the quadrat level. The results indicate that the comparison varies with scale. Though less addressed in previous research and not statistically significant, the residential zones have higher average and median ecosystem services values than the other land use. The result suggests a potentially important contribution of dispersed green space (like private yards) to urban ecosystem services. For a more comprehensive and precise evaluation of ecosystem services of urban forests, further research considering heterogeneity, scale effect, and varieties of green space type are needed.

The results also provided insight for practice. We identified a mismatch of air pollutants removal and emission across land use types that the air cleaning services of urban forests in commercial areas should be improved. Furthermore, a species-specific method can help in making urban planning aimed at increasing ecosystem services.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13010067/s1. Table S1: Main parameters of i-Tree Eco input for this research (denote: "a", customized in this study; "b", replaced with local parameter value via i-Tree Database), Table S2: Average values of ecosystem services of each land use at quadrat and single-tree level, Table S3: Median values of ecosystem services of each land use at quadrat and single-tree level, Table S4: Chi-square statistics of comparison of structure metrics across land use classes by Kruskal–Wallis rank-sum test (the level of significance is denoted by asterisks: no asterisk, $p \geq 0.05$; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$).

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