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Quantifying Regulating Ecosystem Services of Urban Trees: A Case Study of a Green Space at Chungnam National University Using i-Tree Eco

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Abstract: Urban green spaces (UGSs) provide numerous ecosystem services (ESs) that are essential to the well-being of the residents. However, these services are often neglected in regional urban development and spatial planning. This study quantified the ESs of a 10.25 ha UGS at Chungnam National University, Daejeon, Republic of Korea, comprising 27 species with 287 tree individuals, using i-Tree Eco. Key regulating ESs investigated included air pollution removal, carbon storage and sequestration, oxygen production, energy use reduction, avoidance of surface runoff, and replacement and functional values. Results revealed significant annual environmental benefits: 131 kg air pollutants removed (USD 3739.01 or ₩5.16 M), 1.76 Mg carbon sequestered, which is equivalent to 0.18 Mg CO_2 ha^{-1} yr^{-1} (USD 289.85 or ₩0.40 M), 2.42 Mg oxygen produced, energy savings (including carbon offset) valued at USD 391.29 (₩0.54 M), and 203 m^3 reduction in surface runoff (USD 413.09 or ₩0.57 M). The annual total benefits of these urban trees amounted to USD 4833.86 (₩6.67 M), USD 16.83/tree, or USD 0.089/capita. Additionally, these trees had replacement and functional values estimated at USD 311,115.17 (₩429.3 M). The study underscores that species selection and abundance of urban trees are fundamental for maximizing the ES delivery in urban areas, highlighting the role of UGSs in ecological and economical sustainability in cities. These insights are valuable for urban planners and policymakers to optimize benefits of UGSs in cities.

Keywords: ecosystem services; valuation; carbon sequestration; air pollutant removal; surface runoff reduction

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1. Introduction

UGSs play a crucial role within any city, given their ability to offer a multitude of ESs to a diverse set of stakeholders [1,2] including regulating, provisioning, supporting, and cultural services [3,4]. UGS identity is shaped by design and nature, exploring how plants are used as spatial elements in design and how natural plant communities (unique species and seasonal rhythms) contribute to green spaces [5]. Also, they usually reflect political, social, and aesthetic ideals over time, as well as an economic perspective, which evolves from manipulation and beautification in efforts to mimic nature [6]. For instance, in an economic context, Huang et al. [7] explored the relationship between the economy and UGSs at various quantiles in 283 cities in China and showed a positive relationship of areas covered with green spaces with economic growth. The study suggests that cities with larger green spaces might experience higher economic growth. Conversely, increasing population and human-induced activities which are among the downsides of urbanization, contribute to groundwater depletion, as reported by Ramaiah and Avtar [8]. Their study confirmed that the depletion of groundwater augmented the deterioration of UGSs by causing inadequate and irregular watering. Impacts of climate change have also made cities vulnerable to serious environmental problems like flooding, heat island effects, water scarcity, and biodiversity loss [9,10]. UGSs also contribute to achieving climate targets by conserving and augmenting carbon sinking [11–13], stormwater mitigation through avoidance of surface runoff [14–16], and air pollution removal [17–19]. It is clear that a green space's capacity to deliver ESs is context-dependent, and significant variations are based on its size and type [20], the political ecology [21,22], and economic conditions [7,23]. Fine-scale analysis offers unique insights into the benefits provided by individual trees and small groups of trees, often overlooked in broader studies. It is therefore necessary to understand the ESs provided by UGSs within the context of public institutions such as national universities.

According to a UN report in 2019, there is a 95% likelihood that around 68% of the global population resides in urban areas [24]. Urban activities are said to be a major contributor to climate change, responsible for an estimated 71% of carbon dioxide emissions linked to energy consumption [25]. South Korea has developed an ambitious plan to achieve carbon neutrality by 2050, which includes enhancing urban carbon absorption through UGS expansion [26,27]. By 2030, the national objective for reducing greenhouse gas emissions targets upland forests and UGSs to account for 96% of the overall carbon sink goals. Hence, the development and execution of effective strategies for this expansion are imperative, and enhancing the carbon storage and sequestration capacities of UGSs is crucial for effectively balancing carbon emissions [28]. A holistic approach in estimating ESs is thus important in determining the benefits of UGSs, particularly on carbon stock and sequestration.

Despite the recognized potential of UGSs in delivering a multitude of ESs, their integration into urban design and planning remains suboptimal [29–31]. This gap is largely due to a lack of comprehensive, empirical research that provides robust, standardized, and accessible data on the quantifiable benefits of UGSs. Traditional approaches to assessing ESs have often been fragmented and limited in scope, encompassing direct field measurements, biodiversity studies, and valuation studies, among others. However, there is a critical need for a holistic methodology that combines these approaches to provide accurate, actionable insights into the ecosystem services provided by urban trees. Such an approach is essential for making informed decisions, justifying investments, enhancing environmental quality, supporting climate action, and advancing sustainable urban planning.

i-Tree^{TM} stands as one of the emerging tools for comprehensive assessments of UGSs, with South Korea having been included as a supported region of i-Tree since 2019. It is a peer-reviewed software that operates through a systematic process that involves field data collection, analysis, and reporting to assess the structure, function, and value of UGSs. Raum et al. [32] found that i-Tree projects led to a greater understanding of urban forests and increased appreciation for their benefits. In particular, the tool is useful for assessing urban forest structures, quantifying carbon capture and sequestration, removing air pollutants, reducing stormwater runoff, and determining the economic value attributed to these services [28,33].

The purpose of this study contribute to this assessment by utilizing the i-Tree Eco model to quantify and value the regulating ecosystem services provided by urban trees in a specific context—a green space at Chungnam National University, South Korea. The study explores the regulating ES potential of an urban green space at Chungnam National University using i-Tree Eco. While i-Tree Eco has been widely used globally, this study tailors the model to the specific ecological and climatic conditions of the region, providing more accurate and relevant data on ecosystem services. It aims to estimate and value regulating ESs, such as air pollutant removal, carbon storage and absorption, oxygen generation, reduction in energy use, reduction in surface runoff, and replacement value. This analysis intends to address the following research questions: What quantities of air pollutants are removed by the urban green space at CNU? To what extent do the trees contribute to carbon storage and sequestration, and how much oxygen do they produce? Additionally, how does the presence of this green space influence energy consumption through cooling effects, and how effective is it in managing surface runoff to reduce flood risks? Finally, what is the economic value of the ecosystem services provided by these trees, and what would be the replacement cost if the trees were removed for development or other interventions? The study hypothesizes that a certain urban green space at the university significantly contributes to the removal of air pollutants, provides a substantial carbon storage and absorption and oxygen production, effectively reduces energy consumption and surface runoff, and that considerable replacement value following human intervention or infrastructure development is required. The findings of the study could provide valuable insights for urban planners and policymakers to optimize the ecosystem benefits of UGS structures and composition in the university.

2. Materials and Methods

2.1. Site Description and Stand Characteristics

This study was conducted in a 10.25 ha campus urban green space located in Chungnam National University (CNU), Daejeon Metropolitan City, in the central region of South Korea (see Figure 1). Daejeon City covers a total land area of 540 km², with over 50% of this area covered by forests. Although the majority of the forested area lies outside the city, some fragmented forest patches are present within its boundaries [34]. Coniferous forests dominate, accounting for 51% of the total forested area, while broadleaf and mixed forests are the second and third most common types, respectively. The forested regions are primarily composed of species such as *Pinus densiflora* Siebold & Zucc., *Pinus koraiensis* Siebold & Zucc., and *Pinus rigida* Mill. [35].

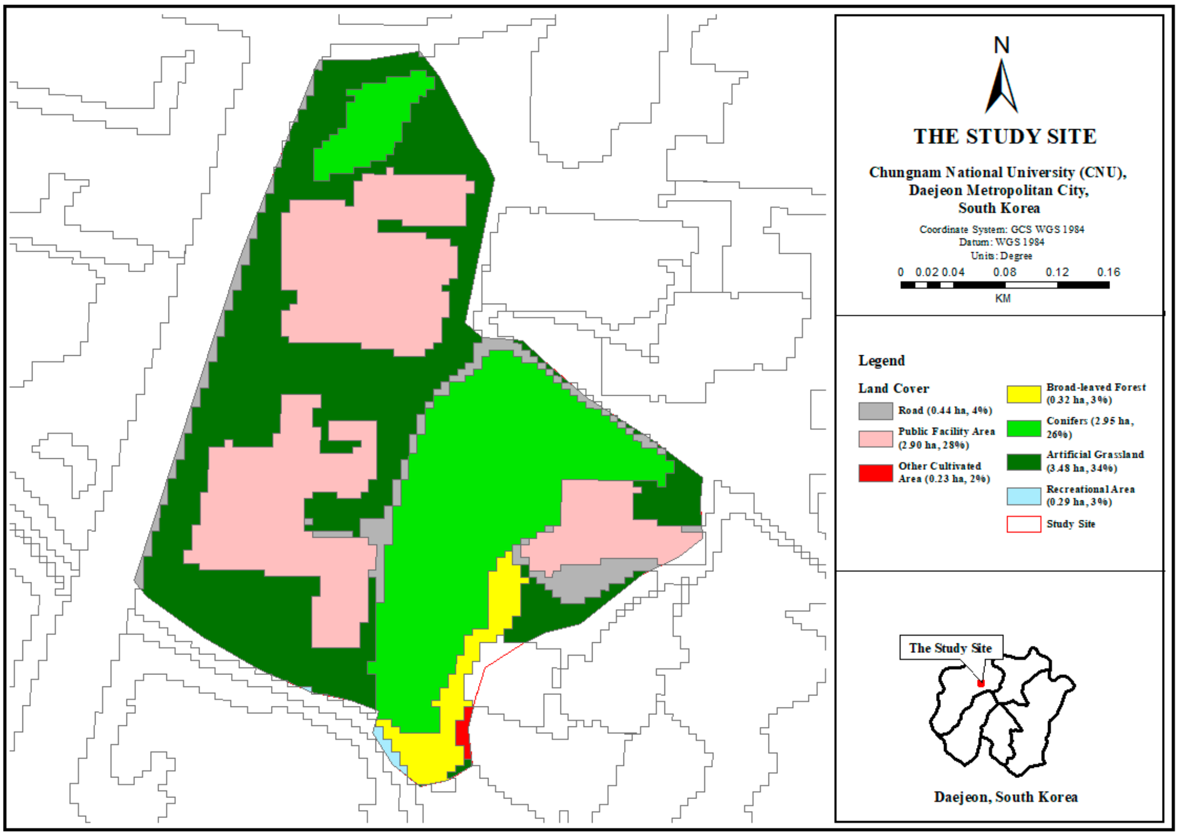

Figure 1. Location of the studied green space in Chungnam National University, Daejeon, South Korea (land cover basemap available from the Korea Environmental Spatial Information Service, accessible at https://egis.me.go.kr/, accessed on 4 July 2024).

The study area features a gentle slope located at an elevation of 72.2 to 128 m above sea level, has a topography characterized by a basin surrounded by mountains on all sides, and the outline of mountains is clearly visible from all cardinal directions. Based on 30-year climatological data (1992–2022) obtained from a nearby Automated Synoptic Observation

System (ASOS) facility as cited by Carayugan et al. [36], the surface temperature shows pronounced seasonal variations. Normal, minimum, and maximum temperatures average 13.2 °C, 8.4 °C, and 18.3 °C, respectively. Annual precipitation averages 1344 mm, with 60% occurring between July and September, and the remaining 40% evenly distributed throughout the rest of the year. Mean relative humidity ranges from 62.3% to 73.2%, total annual evaporation from 813.3 mm to 1475.2 mm, mean wind speed from 1.4 m s^{-1} to 2.7 m s^{-1}, and total annual solar radiation from 4351.7 MJ m^{-2} to 5954.0 MJ m^{-2}.

Prior to the estimation of ecosystem services, urban tree structural characterization was conducted following the i-Tree Eco field measurement manual [37,38]. Tree structural measurements included diameter at breast height (DBH), tree height (TH), crown base height (CBH), and crown width (CW). Crown health was assessed visually based on the number of dead branches (i.e., dieback) in the tree's crown and can be estimated as dieback or condition. Derived variables such as leaf area and leaf biomass, as well as subsequent analyses including importance value (IV), species distribution, and dominance, were estimated using i-Tree. The proportion of tree cover in the target site was approximately 31% (2.99 ha.), with a total of 287 trees. Among these, the three most dominant species were *P. densiflora* Siebold & Zucc (20.6%), *P. rigida* Mill. (13.8%), and *Juniperus chinensis* L. (9.2%). *Quercus acutissima* Carruth. had the highest accumulated leaf area, covering 1891.7 m^2. Trees with a DBH class of 15.2–30.5 cm dominated the area (about 44%), followed by trees with one of 30.5–45.7 cm (approx. 25%). Tree density per land cover revealed that conifer stands had the highest density, with 43.7 trees/ha, closely followed by broadleaf stands with 41.2 trees/ha. Areas designated for public facility had notably lower tree density, with 9.7 trees/ha. Crown health conditions varied across species, wherein the majority were notably good to excellent. The importance value (IV), calculated by the sum of percent population and percent leaf area [39], indicated that *P. densiflora* Siebold & Zucc and *P. rigida* Mill. had the highest IVs at 31.2 and 22.7, respectively. The geographic distribution of urban trees in a selected green space at CNU comprised a mix of native and exotic tree species. Approximately 77% of the total tree species were native to Asia, while 20% were exotic species, the majority originating from North America.

2.2. Sample Plots and Field Data Measurements

Pre-stratified random plots were created to collect tree structural information of the study area. QGIS software (version 3.14) with the spatial analysis tools was utilized to create stratified random sample plots. Stratification was based on land cover types, which included conifers stands (2.59 ha), artificial grassland (3.48 ha), public facility areas (2.90 ha), roads (0.44 ha), recreational areas (0.29 ha), broadleaf forest (0.32 ha), and other cultivated areas (0.23 ha). A total of 100 plots were set up across the 10.25 ha study area, each plot with a radius of 5.64 m (area = 100 m^2) as recommended by [40]. All trees with $\geq$5 cm diameter at breast height (DBH) measured at a height of 1.2 m above the ground were included in the study. DBH was measured based on South Korea's National Forest Inventory (NFI) protocol. Total height of the tree was measured using a laser distance measuring device (Haglof Vertex IV-BT-360, Haglöf Sweden, Langsle, Sweden) manufactured by Haglöf Sweden. For standing dead trees, downed living trees, or severely leaning trees, height was measured as the vertical distance along the main stem from ground to tree top. The live crown base is the point on the main trunk perpendicular to the lowest live foliage on the last branch that is included in the live crown. In i-Tree Eco, crown diameter is referred to as crown width and is measured in two cardinal directions—north–south and east–west—perpendicularly to the stem [37,41]. Crown diameter is measured in two perpendicular directions (east–west and north–south) and averaged to obtain the crown width. Ground cover is visually assessed for the proportion of paved, impervious, and exposed soil within the plot [42]. Die-back and crown missing, factors that determine the health of the crown, were recorded as 0%–100% by observing the proportion of dead branches and the abundance of the crown, respectively, out of the total value. The i-Tree Eco Field Guide defines crown light exposure (CLE) as "the number of sides of the tree's crown receiving light from above or from the side". Obstructions to light are defined as "any parts of an adjacent tree crown or building that are (a) overtopping any part of the crown side, or (b) within one average crown width of the measured tree's stem and are at least as tall as the measured tree". CLE is rated on a scale from 0 to 5, where 0 indicates that the tree does not receive light from any side, and 5 indicates that the tree receives light from all directions, including from above. Scaling is categorized into five directions (north, south, east, west, and vertical) relative to the center of the tree crown.

2.3. Estimation and Valuation of Ecosystem Services (ESs)

2.3.1. Air Pollution Removal

To quantify air pollution removal by urban trees within the study site, the analysis used by i-Tree Eco focused exclusively on the dry deposition (air pollution removal) during non-precipitation periods throughout the year [43,44]. Based on a report by Lin et al. [45], the dry deposition of air pollutants to trees was evaluated using dry deposition velocity and air pollutant concentrations, with the assumption that these pollutants do not adversely affect plant functions. For nitrogen dioxide (NO_2), temperature and leaf area index (LAI) were identified as the most influential factors, with temperature exhibiting a higher mean impact (μ) than LAI. However, temperature's relationship with the dry deposition velocity (Vd) of NO_2 was less linear compared to LAI, as evidenced by its higher standard deviation (σ). In contrast, relative humidity (RH), wind speed, and photosynthetically active radiation (PAR) had lower μ values compared to temperature and LAI, indicating their more moderate and comparable effects on the Vd of NO_2. These variables also showed higher σ values than LAI, suggesting a less linear relationship with the Vd of NO_2. Atmospheric pressure had a minimal effect, as reflected by its low μ and σ. For the dry deposition velocities of sulfur dioxide (SO_2) and ozone (O_3), a similar ranking pattern emerged based on μ values: temperature > RH > LAI > wind speed > PAR > pressure. Among these, temperature had the highest μ and σ, indicating its significant impact on model outcomes and a highly non-linear relationship with Vd. RH, LAI, wind speed, and PAR displayed intermediate positions on the (μ, σ) plane, while pressure had a negligible effect.

Urban tree structure information, including tree cover, leaf area index (LAI), and percent evergreen, was input into the model alongside local weather and pollution data. Boundary layer height data were also incorporated to estimate the percentage improvement in air quality resulting from the pollution removal by trees. The pollutant flux (F; in $g\ m^{-2}s^{-1}$) were calculated as the product of the deposition velocity (V_d; in $m\ s^{-1}$) and pollutant concentration (C; in $g\ m^{-3}$):

$$F = V_d\, C \tag{1}$$

Deposition velocities were set to zero in the precipitation period [46]. For CO, NO_2, SO_2, and O_3, deposition velocities were calculated as the inverse of the sum of aerodynamic resistance (R_a), quasi-laminar boundary layer resistance (R_b), and canopy resistance (R_c): $Vd = (R_a + R_b + R_c)^{-1}$. The aerodynamic resistance is independent of the air pollutant type. It was calculated using meteorological data, while the quasi-laminar resistance and canopy resistance were calculated for each air pollutant [47]. Hourly canopy resistance was calculated using the following equation: $1/R_c = 1/(r_s + r_m) + 1/r_{soil} + 1/r_{t:}$, where r_s is the stomatal resistance; r_m is the mesophyll resistance; r_{soil} is the soil resistance, and r_t is the cuticular resistance [47,48]. The default values (the multipliers) of air pollutant removal rates ($g\ m^{-2}\ yr^{-1}$) and monetary values ($USD\ m^{-2}\ yr^{-1}$) for a unit tree cover were derived from i-Tree Eco analyses in the conterminous United States in 2010 [44]. The value of each pollutant was based on approximately USD 0.0013 (₩1.81) g^{-1} $year^{-1}$ of CO, USD 0.0041 (₩5.64) ton $^{-1}$ $year^{-1}$ of NO_2, USD 0.027 (₩37.75) ton $^{-1}$ $year^{-1}$ of O_3, USD 0.0063 (₩8.68) ton $^{-1}$ $year^{-1}$ of PM_{10}, USD 0.95 (₩1310.36) ton $^{-1}$ $year^{-1}$ of $PM_{2.5}$, and USD 0.0015 (₩2.05) ton $^{-1}$ $year^{-1}$ of SO_2.

For PM_{10}, as reported by Nowak [49], i-Tree Eco uses a median deposition velocity of 0.0128 m/s during the leaf-on season [50]. The base particle deposition velocity (Vd) was set to 0.064, based on a leaf area index (LAI) of six and a 50% resuspension rate of particles back into the atmosphere [51]. This base Vd is adjusted according to the actual LAI and parameters for leaf-on versus leaf-off seasons. On the other hand, for $PM_{2.5}$, hourly deposition velocities and resuspension rates vary with wind speed, as detailed by Nowak et al. [52].

In terms of volatile organic compounds (VOCs), emission levels are influenced by factors such as vegetation genus, leaf dry weight biomass, air and leaf temperature, and other environmental conditions, as reported by Hirabayashi [53]. i-Tree Eco estimates the hourly emissions of isoprene (C5H8) and monoterpenes (C10 terpenoids) by genus for each land use type, based on field sampling of various vegetation types, including deciduous and evergreen trees and shrubs. These hourly estimates are aggregated for the entire year, the leaf-on period, each month, and daytime within each month, and then averaged for the year, depending on the type of tree or shrub (deciduous or evergreen). Additionally, the annual total VOC emissions by genus for each land use are summarized for individual trees, species within the analysis domain, and species within land use types.

Hourly weather data and pollution data were obtained from the Daejeon Metropolitan City Yuseong-gu Meteorological Observatory (KOR-133), with boundary layer data sourced from the nearest monitoring station. These data included hourly pollution concentration measurements for ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), particulate matter with diameters between 2.5 and 10 µm (PM_{10}), and particulate matter with diameters less than 2.5 µm ($PM_{2.5}$). The dry deposition model of i-Tree Eco employs tree data, hourly weather information, and pollution concentration levels to quantify the hourly amount of pollution removal and the corresponding percent improvement in air quality [31,44].

2.3.2. Carbon Stock and Sequestration

i-Tree Eco calculates the urban forest carbon storage (CS) and gross carbon sequestration (GCS) based on a peer reviewed tree growth model and a biomass equation, which are defined by the relationship between tree species, diameter at breast height (DBH), crown coverage, and tree health [54,55]. i-Tree Eco utilizes a total of 150 allometric equations, each representing a different tree species. In instances where there is no available equation for a given tree species, genus level aggregate equation was used, if available. However, in the absence of a genus level equation, the family level aggregate equation was used [56]. This study followed the recommendation of Nowak [57], that urban trees had on average 20% less biomass than allometric equations predicted for traditional forest trees; therefore, the biomass estimate was multiplied by 0.8 to reduce this error. The monetary value, as calculated by i-Tree Eco, is based on current tree age estimates and tree life expectancy using simple allometric equations [58], and a 1.4% discount rate [59]. The economic value conversion was determined as the present value of the discounted flow of the annual monetary value of the ecosystem service indicator over the expected lifetime of the tree, which amounts to USD 164.85 (₩228,185) per metric ton of Carbon.

2.3.3. Energy Savings

Trees can have a significant impact on changes in the energy consumption by buildings [60]. Energy savings were measured as the results of the effects of trees on building energy use and consequent effects on carbon dioxide emissions from power plants. Variables such as tree species, height, crown missing, distance, and direction of trees in relation to buildings were used to estimate the impact of trees on energy use. Direction was measured by the angle of the tree relative to the nearest part of the building, while distance was determined by the shortest distance from the tree to the closest part of the building [49]. According to a study conducted by McPherson and Simpson [61], trees at a distance within 18 m of buildings have an impact on energy used, therefore all trees with distance $\leq$ 18 m were noted. Estimates of tree effects on energy use are derived from field measurements that consider factors like tree distance and direction relative to residential buildings with air conditioning. These measurements help assess the specific impact of trees on cooling loads and heating requirements throughout the year. For this study, the economic value of energy savings was converted to USD 55.20 (₩76,390) per MWH (megawatt hour) based on the default values of a reference city [62].

2.3.4. Oxygen Production

Annual net oxygen production in trees occurs during photosynthesis and is directly related to the carbon absorbed. Tree net oxygen production is determined by the difference between the oxygen produced during photosynthesis and the oxygen consumed during plant respiration [63]. While this benefit is commonly cited, it is comparatively less important due to the vast amount of oxygen already present in the atmosphere and the substantial oxygen production by aquatic systems [64]. The tool directly estimated the amount of oxygen produced from carbon sequestration, which is linked to the tree biomass accumulation potential [65,66], taking into account atomic weights, and was guided by this equation:

$$\text{net } O_2 \text{ release (kg/yr)} = \text{net C sequestration (kg/yr)} \times 32/12 \tag{2}$$

i-Tree assigns a value of USD 0 per ton for oxygen production. This is because the oxygen production value of trees is considered insignificant due to the vast quantity of oxygen already present in the atmosphere.

2.3.5. Avoided Runoff

This is the amount of water held in the tree canopy and re-evaporated after the rainfall event (avoided runoff) and not entering the water treatment system. In i-Tree, precipitation data are required for avoided runoff modeling. Meteorological data were based on the 2018 weather information from the Daejeon Yuseong-gu Meteorological Observatory (KOR-133), and the total annual precipitation at the study site was 154.1 cm.

The i-Tree Eco model builds upon the framework established by Hirabayashi [67]. To estimate annual surface runoff, two scenarios were compared: one with vegetation and one without. In the first scenario, both vegetated and non-vegetated areas were included, while in the second scenario, only the non-vegetated areas were considered. For each scenario, runoff was calculated hourly and then multiplied by the area of impermeable surfaces. Generally, the scenario with vegetation results in reduced runoff, as plants intercept, store, and evaporate some of the rainfall. The difference between the two scenarios represents the amount of water that vegetation effectively prevents from running off the surface. Below is the equation used by i-Tree Eco to compute annual avoided runoff, AvR_a (m^3):

$$AvRa = \sum Ri_t \times IA_2 - \left(\sum Rv_t \times IAv_1 + \sum Rg_t \times IAg_1\right) \tag{3}$$

where Ri_t = surface runoff from impervious cover in scenario 2 at time t (m hr^{-1}); IA_2 = impervious cover in scenario 2 (m^2); IAv_1 = under canopy impervious cover in scenario 1 (m^2) and; IAg_1 = outside canopy impervious cover in scenario 1 (m^2). The avoided runoff is valued using the cost of managing stormwater through traditional infrastructure, such as the construction and maintenance of stormwater facilities [68].

2.3.6. Replacement and Functional Values

This is the value of the trees based on the physical resource itself (e.g., the cost of having to replace a tree with a similar tree). The value is determined within i-Tree Eco according to the CTLA (Council of Tree and Landscape Appraisers) method. This method estimates the replacement cost of a tree based on its size, species, and condition. The resulting structural value is commonly used for monetary settlements in legal disputes involving tree damage or loss, insurance claims, and property tax assessments. The valuation used is guided by the Capital Asset Value for Amenity Trees (CAVAT) method [69]. The replacement cost method assesses the economic worth of an ecosystem service by calculating the associated cost of replacing the service using human-made substitutes [70]. One notable advantage of using this method in this context is its focused evaluation of the microclimate benefits, allowing for integration with value assessments of other ecosystem services [71].

2.3.7. Statistical Analysis

Correlations between tree structural attributes—such as basal area, leaf area index (LAI), abundance, cover, and density—and ecosystem services were examined to gain insights into how these attributes influence the various ecosystem services provided by urban forests. Analysis was performed using SPSS 26. Prior to conducting the correlation analysis, the normality of the data for all variables (ecosystem services) was assessed using the Shapiro–Wilk test. Additionally, Levene's test for homogeneity of variances was conducted to assess equal variances across groups. A Pearson correlation coefficient was computed to determine which tree attributes were more influential on environmental effects. A positive Pearson correlation coefficient indicates that as the value of one variable increases, the value of the other variable also tends to increase, assuming a linear relationship between the variables. For variables that did not meet the assumptions of normality and homoscedasticity (equal variances), Spearman's rank correlation was used as an alternative. A positive Spearman correlation between structural attributes and ecosystem services indicated that higher structural attributes are associated with better ecosystem services. Meanwhile, a stepwise regression analysis was performed to identify the primary predictors of hydrological effects in the study area.

3. Results

3.1. Estimated and Valued Ecosystem Services

3.1.1. Air Pollution Removal

Considering all assessed pollutants, including O_3, CO, NO_2, $PM_{2.5}$, PM_{10}, and SO_2, a total of 131 kg of air pollutants was removed annually with an associated economic value amounting to USD 1498.89 (₩2.07 million). Among these pollutants, urban trees were most effective in removing ozone (73.024 kg/yr), followed by PM_{10} (31.404 kg/yr) (see Figure 2). In terms of emissions, urban tree composition and density emitted an estimated 64.73 kg of volatile organic compounds (VOCs) per year, consisting of 33.03 kg of isoprene and 31.70 kg of monoterpenes. On the species level, *Q. acutissima* Carruth. was the major contributor to VOC emissions accounting to 60.74% of the total emissions from the study area. The highest SO_2 uptake was observed during summer (0.778 kg).

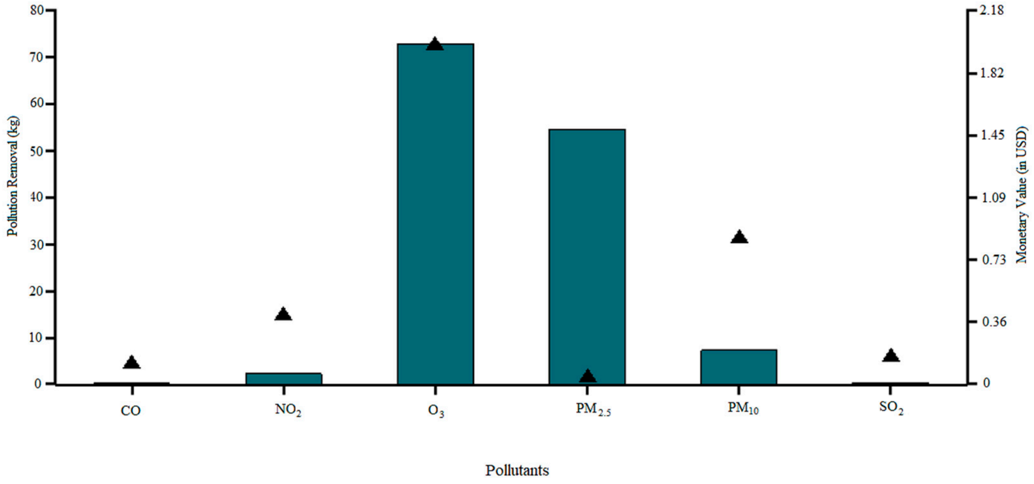

Figure 2. Annual pollution removal (triangles) and values (bars) by urban trees.

3.1.2. Carbon Sequestration (Cseq) and Stock (C Stocks)

The green space at CNU had a total sequestered CO_2 of approximately 1.764 metric tons CO_2 yr^{-1} (0.18 metric tons CO_2 ha^{-1} yr^{-1}), with *Q. acutissima* Carruth. (0.22 ton/ha/yr) and *P. densiflora* Siebold & Zucc. (0.19 ton/ha/yr) species exhibiting the highest sequestration rates and values (see Table 1). The highest carbon sequestration was found in artificial grassland cover (0.69 ton/yr) and coniferous stands (0.57 ton/yr). Taking into account the amount of respiration and decomposition, the net annual carbon sequestration in the urban forest was about 906.9 kg CO_2. The results of Spearman's rank correlation revealed that, among the analyzed variables, the basal area showed the highest positive correlation with Cseq (r = 0.791, $p < 0.000$). This was followed by the canopy cover (r = 0.74, $p < 0.000$), LAI (r = 0.691, $p < 0.000$), and tree density (r = 0.674, $p < 0.000$). With regard to the monetary benefit, the economic value of the removed CO_2 was USD 291.09 (₩402,000), reflecting sequestration services, such as improved air quality.

Table 1. Carbon sequestration per species.

Species	Tree Density (tree/ha)	Canopy Cover (m^2)	LAI (m^2)	Basal Area (m^2)	Cseq (Mg/yr)
Pinus densiflora Siebold & Zucc.	59	439.4	1243.6	1.80	0.19
Pinus rigida Mill.	40	470.1	1053.6	1.20	0.17
Junipers chinensis L.	26	23.1	69.6	0.20	0.15
Acer palmatum Thunb.	20	190.8	989.8	0.60	0.07
Liriodendron tulipifera L.	16	98.9	824.8	0.30	0.13
Quercus aliena Blume	12	62.9	227.7	0.60	0.06
Zelkova serrata (Thunb.) Makino	12	132.8	858.8	0.30	0.07
Chionanthus retusus Lindl. & Paxton	11	20.0	70.1	0.09	0.03
Pinus koraiensis Siebold & Zucc.	10	144.9	1201.7	0.20	0.03
Quercus acutissima Carruth.	10	272.5	1891.7	0.60	0.22
Abies holophylla Maxim.	7	23.3	138.2	0.10	0.01
Metasequoia glyptostroboides Hu & Cheng	7	106.8	1100.9	0.60	0.06
Acer buergerianum Miq.	5	55.0	566.5	0.20	0.07
Ginkgo biloba L.	5	29.4	176.1	0.10	0.01
Acer pseudosieboldianum (Pax) Komarov	5	20.1	35.9	0.20	0.06
Distylium sp.	5	13.4	29.4	0.08	0.05
Quercus variabilis Blume	5	47.9	254.5	0.10	0.05
Prunus serrulata Lindl.	5	84.5	471.0	0.20	0.06
Prunus sargentii Rehder	5	92.6	361.0	0.50	0.14
Lespedeza bicolor Turcz.	3	4.8	5.7	0.08	0.01
Magnolia kobus DC.	3	1.5	22.7	0.08	0.03
Pinus strobus L.	3	.6	1.8	0.06	0.01
Prunus mume (Siebold) Siebold & Zucc.	3	22.9	68.9	0.20	0.01
Cercis chinensis Bunge	3	4.0	5.9	0.09	0.01
Alnus incana (L.) Moench	2	19.2	40.3	0.08	0.01
Fraxinus chinensis Roxb. ssp.	2	29.0	121.8	0.10	0.03
Ulmus parvifolia Jacq.	2	40.7	142.4	0.10	0.06

3.1.3. Oxygen Production

The annual estimated oxygen production of the studied green space was 2.418 metric tons of O_2. Among the observed species, *Q. acutissima* Carruth., *J. chinensis* L., and *L. tulipifera* L. were the top three contributors to oxygen production (see Table 2). *Q. acutissima* Carruth. had the highest annual oxygen production, totaling 460.87 kg. *J. chinensis* L. produced 383.29 kg of oxygen annually and was the most populous species with 26 individuals. Despite its relatively small leaf area (0.02 ha), its high oxygen production emphasized its efficiency and suitability for urban environments where space is limited. The amount of oxygen produced had moderate correlation with carbon storage (r = 0.623; $p = 0.003$) and LAI (r = 0.458; $p = 0.026$).

Table 2. Top 20 oxygen producing species at the study site.

Species	Oxygen Production (kg)	Carbon Storage (Mg)	Number of Trees	Leaf Area (ha)
Quercus acutissima Carruth.	460.87	8.0	10	0.48
Juniperus chinensis L.	383.29	1.7	26	0.02
Liriodendron tulipitera L.	318.37	2.5	16	0.22
Zelkova serrata (Thunb.) Makino	157.84	1.7	12	0.19
Acer buergerianum Miq.	155.20	2.0	5	0.15
Acer pseudosieboldianum (Pax) Komarov	154.08	1.4	5	0.01
Ulmus parvifolia Jacq.	143.14	0.5	2	0.03
Distylium sp.	139.97	0.4	5	0.01
Prunus serrulata Lindl.	129.06	3.4	5	0.12
Acer palmatum Thunb.	118.66	5.1	20	0.25
Quercus variabilis Blume	101.84	1.5	5	0.06
Metasequoia glyptostroboides Hu & Cheng	96.41	2.5	7	0.25
Chionanthus retusus Lindl. & Paxton	72.85	0.2	11	0.02
Magnolia kobus DC.	66.83	0.2	3	0.01
Fraxinus chinensis Roxb. ssp.	64.07	0.3	2	0.02
Pinus koraiensis Siebold & Zucc.	52.74	1.1	10	0.32
Quercus aliena Blume	40.81	2.0	12	0.06
Ginkgo biloba L.	32.60	0.4	5	0.05
Lespedeza bicolor Turcz.	26.15	0.01	3	0.00
Cercis chinensis Bunge	12.14	0.01	3	0.00

3.1.4. Trees and Building Energy Savings

Urban trees are estimated to reduce energy-related costs from residential buildings by USD 93.41 (₩129,000) annually. Trees also provide an additional USD 293.25 (₩405,000) in value by reducing the amount of carbon released by fossil-fuel based power plants (a reduction of 1.78 metric tons of carbon emissions) (see Tables 3 and 4).

Table 3. Annual energy savings due to trees near residential buildings.

	Heating	Cooling	Total
MBTU [a]	68.409	N/A	68.409
MWH [b]	0.519	1.166	1.685
Carbon avoided (Mg)	1.597	0.178	1.775

[a] MBTU—million British thermal units; [b] MWH—Megawatt-hour; Mg = milliongrams (or 1 metric ton).

Table 4. Annual monetary savings [a] (USD) in residential energy expenditure during heating and cooling.

	Heating	Cooling	Total
MBTU [a]	0.44	N/A	0.44
MWH [b]	29.66	66.61	96.27
Carbon avoided (Mg)	272.53	30.41	302.94

[a] Based on the prices of USD 55.31 per MWH and 8.58 per MBTU; million British thermal units (MBTU) [b] MWH—Megawatt-hour; Mg = milliongrams (or 1 metric ton).

3.1.5. Avoided Runoff

Urban trees in a study site helped reduce runoff by an estimated 203 cubic meters per year at 154.1 cm total annual precipitation (see Figure 3). Considering the mean annual precipitation of the entire city of Daejeon (mean annual precipitation, 1344 mm), a 10.25 ha urban green space at CNU could offset 2.8×10^{-7} cubic meters of runoff annually. In the species level analysis, *Q. acutissima* Carruth. (AvR_a = 32.44 m^3/yr), *Pinus koraiensis* Siebold & Zucc. (AvR_a = 21.92 m^3/yr), and *P. densiflora* Siebold & Zucc. (AvR_a = 21.58 m^3/yr) were the most efficient species in reducing surface runoff. The Pearson correlation revealed that runoff reduction ecosystem services by urban trees (RRES) have a very strong positive relationship with LAI (r = 0.965; $p < 0.000$), and moderate correlation with abundance (r = 0.613; $p = 0.006$). Furthermore, stepwise regression analysis indicated that leaf area has the highest influence on hydrological effects ($r^2 = 0.932$), demonstrating that this parameter explains 99% of the variation in RRES in the study area.

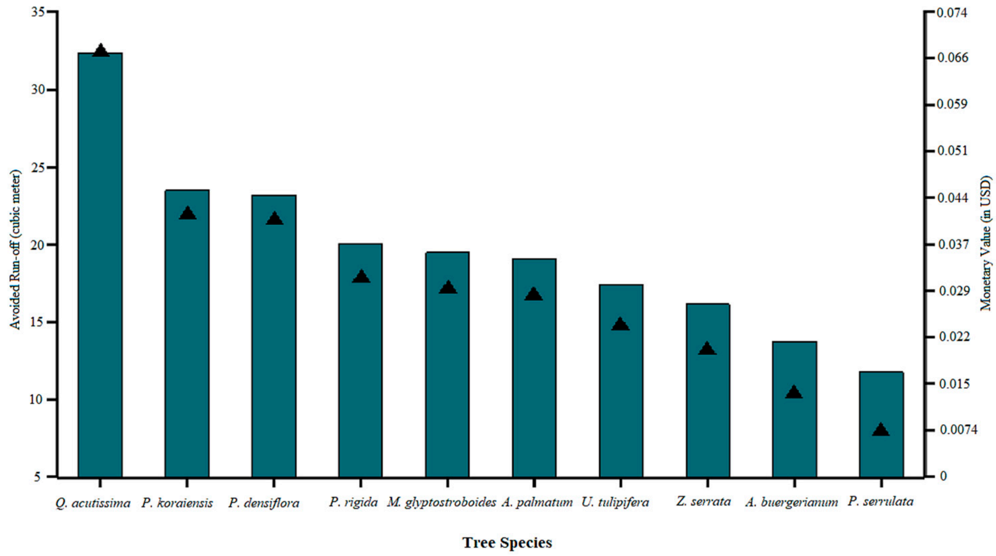

Figure 3. Runoff reduction ecosystem services (RRES) by urban trees (triangles) and values (bars).

3.2. Replacement and Functional Values

The total replacement value of the present urban trees was USD 310,850.59, equivalent to ₩429.3 M (USD 300,496.15 (₩415 million) for the replacement value itself and USD 10,354.40 (₩14.3 million) for carbon storage). In addition, the total functional values of urban trees amounted to USD 4827.56 (₩6.668 million) of which benefits from pollution removal, USD 3736.27 or ₩5.16 M (77.38%), had the greatest contribution (see Figure 4). The results highlighted the direct economic benefits of urban trees in improving air quality and overall environmental quality in urban settings. This was followed by AvR_a (USD 414.18 or ₩0.572 M), energy costs and emission values (USD 386.66 or ₩0.534 M), and Cseq (USD 291.08 or ₩0.402 M). As to the species level, stands of *P. densiflora* Siebold & Zucc. and *P. rigida* Mill. had the highest replacement values amounting to USD 49,332.66 (₩68.14 M) and USD 31,319.80 (₩43.26 M), respectively.

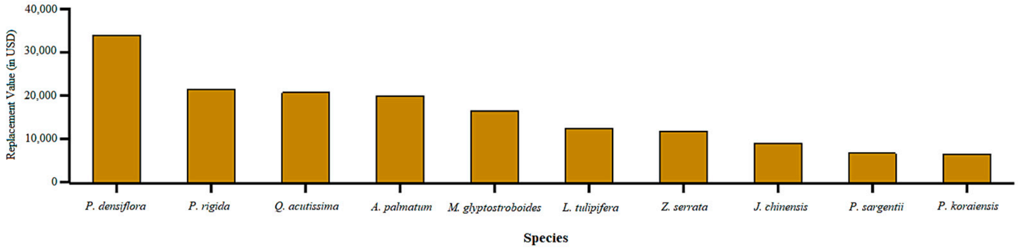

Figure 4. Tree species with highest replacement values.

4. Discussion

The role of UGSs in mitigating air pollution is complex, encompassing both the direct removal of pollutants and the strategic selection of tree species to optimize these benefits. The significant amount of ozone (O_3) removed by urban trees is consistent with studies conducted at the Auburn University in Alabama [33,72], the University of British Columbia [73], and the University of Tokyo [74]. The removal of O_3 is essential, as high concentrations of it affect photosynthetic CO_2 uptake because of its high phytotoxicity and other stresses to plants, especially with increasing temperature [75]. Likewise, trees exposed to primary air pollutants such as SO_2, NO_2, and O_3 show increased susceptibility to pests and diseases [76], highlighting the need for both pest and pollution management strategies. The highest SO_2 uptake during summer was consistent with a study by Kleeman [77], wherein an increasing temperature promotes faster oxidation of SO_2 to form sulfuric acid (H_2SO_4). However, H_2SO_4 remains non-volatile at all ambient temperatures, which significantly hinders its uptake by trees, and, due to stomatal conductance, hinders a tree's adaptation to conserve water [78,79]. VOC emissions vary among species based on their age [80], the season [81], and their amount of leaf biomass (e.g., species such as oaks are known as high isoprene emitters) [82]. On the other hand, VOCs exposed to sunlight and nitrogen oxides (NO_2), can undergo photochemical reactions to form ground-level ozone, which is a harmful pollutant [83]. These insights from the relationship between the pollution removal benefits, species selection, and VOC emissions within urban forests is crucial for effective urban forest management. Urban foresters can strategically choose tree species with lower VOC emissions, thereby reducing role in ozone formation to optimize pollution removal benefits. The captured pollutants influence local climate and atmospheric conditions by lowering the ambient temperature, increasing the humidity through transpiration, and improving the air quality [84,85]. From a public health standpoint, it is crucial to recognize that even minor improvements in air quality attributable to trees can significantly benefit human health [86]. The associated economic value of USD 1498.74 (₩2.07 million), as calculated by i-Tree Eco, reflects the monetary benefits from avoided adverse health incidences and costs stemming from captured CO, NO_2, O_3, $PM_{2.5}$, $PM_{10.5}$, and SO_2 concentration due to pollution removal by trees [87].

Cseq density (0.18 metric tons CO_2 ha^{-1} yr^{-1}) is comparable to green spaces in the cities of Casper, Wyoming (0.20 metric tons CO_2 ha^{-1} yr^{-1}), and Jersey City, NJ (0.21 metric tons CO_2 ha^{-1} yr^{-1}) [88,89]. Good to excellent crown health condition of trees at the study site explained effective carbon storage and sequestration helping to mitigate climate change [90–92]. An effective carbon sequestration function of an urban green space helps reduce atmospheric CO_2 levels, thereby optimizing its capacity to mitigate climate change and its associated impacts [93]. A very strong positive correlation between tree basal area and Cseq, alongside LAI and canopy cover denotes them as indicators for biomass and carbon sequestration [94,95].The monetary benefit or the economic value of the removed C amounts to USD 291.06 (₩402,000). Assigning a monetary value to the carbon sequestration services highlights the economic importance of investing in and preserving green spaces, thereby serving as basis in planning, developing, and evaluating programs for managing UGSs [69,96–98].

Oxygen production by urban trees is a well-documented benefit, intricately linked to carbon storage and photosynthetic activity [63,99]. This relationship suggests that species efficient in oxygen production are also likely to sequester significant amounts of carbon, reinforcing their role in climate change mitigation [100]. The positive correlation of oxygen production with carbon storage was aligned with the reports by Nowak et al. [63] and Duncan and Dasgupta [100]. Accordingly, the net oxygen production by a tree over a year is directly tied to the amount of carbon dioxide absorbed through photosynthesis, which, in turn, correlates with the tree biomass accumulation. Also, the correlation between leaf surface area in photosynthesis and subsequent oxygen release highlights the importance of a canopy cover in maximizing ecological services [101], thereby linking it directly to the overall health benefits associated with UGSs [102,103]. However, the overall benefit is relatively insignificant due to vast and relatively stable amounts of oxygen in the atmosphere and its extensive production by aquatic systems (through marine organisms like phytoplankton) [104], large forests, and extensively vegetated areas [105].

The energy-saving potential of urban trees varies throughout the seasons and can influence building energy consumption through diverse mechanisms. The avoided energy cost by trees in the study area is attributed to the ability of trees to provide shade in summer (reducing air conditioning needs) and windbreak in winter (reducing heating needs). Trees influence energy consumption in buildings through several mechanisms such as shading, evaporative cooling, and wind blocking, hence planting additional trees could double their benefits [106]. During the summer months, trees typically reduce building energy consumption by providing shade and evaporative cooling [107]. A study conducted by Balter et al. [108] found that the air temperature beneath the tree canopy was 2.3 °C cooler compared to temperatures above the canopy. Additionally, the energy consumption for cooling the building floor above the tree canopy was 42% higher than the energy required for cooling below the tree canopy. In winter, the impact of trees on energy use can vary significantly. Strategically placing trees can help reduce heating costs by blocking cold winds, thereby decreasing heat loss from buildings [61,109]. In addition, a dense tree cover can also lead to increased energy consumption by reducing solar gain due to shade, which is crucial for passive heating in colder months [110]. One effective strategy to mitigate this issue is to use deciduous tree species like *Q. acutissima* Carruth. and *L. tulipifera* L., which shed their leaves in winter. While trees offer benefits in reducing heating costs through wind blocking, their effect on energy use in winter depends on their placement and density relative to buildings [111,112].

The associated value of avoided runoff considers the costs that would otherwise be incurred for managing stormwater through infrastructure investments or flood damage repairs. The strong positive relationship of RRES with LAI is consistent with studies by Ross et al. [113] and Ji et al. [114]. The LAI is also identified as one of the variables that substantially reduces the volume of generated runoff in cities based on a literature review by Orta-Ortiz and Geneletti [16]. Understanding the precipitation patterns is essential for assessing the impact of UGSs on managing urban stormwater and flood, and improving water quality [115].

Finally, the assessed functional and replacement value by urban trees highlights the financial investment required to replace its provided ecological services. The replacement value of an urban forest tends to increase with a rise in the quantity and size of healthy trees [116]. Health significantly enhances trees' effectiveness in providing ecosystem services, thereby augmenting their overall economic and ecological value to urban environments [90,92].

5. Conclusions

Quantification of regulating ecosystem services by urban trees revealed significant annual environmental benefits from the urban trees, including the removal of 131 kg of air pollutants (USD 3739.01 or ₩5.16 M), 1.76 Mg carbon sequestered equivalent to 0.18 Mg CO_2 ha^{-1} yr^{-1} (USD 289.85 or ₩0.40 M), 2.42 Mg oxygen produced, energy savings (including carbon offset) valued at USD 391.29 (₩0.54 M), and 203 m^3 produced surface runoff (USD 413.09 or ₩0.57 M). The total annual benefits of these urban trees amounted to USD 4833.86 (₩6.67 M), USD 16.83 per tree, or USD 0.089 per capita. Additionally, the replacement and functional values of these trees were estimated at USD 311,115.17 (₩429.3 M).

Species selection and abundance of urban tree species are fundamental to optimize ecosystem services delivery in urban areas. Carefully selecting a diverse range of tree species that are well-suited to local conditions, and ensuring an abundant and well-distributed urban forest, can significantly enhance air quality, augment carbon uptake, manage stormwater, increase oxygen production, and reduce energy consumption.

Despite the significant role in removing pollutants such as ozone and PM_{10}, it is crucial to strategically select tree species with lower volatile organic compound (VOC) emissions to optimize the air quality benefits of the green space. Trees such as *Q. acutissima* Carruth. emit volatile organic compounds (VOCs), particularly isoprene and monoterpenes, which may contribute to ozone formation under certain conditions. Urban forest management should prioritize selecting tree species with lower VOC emissions. This strategic approach can optimize the overall air quality benefits provided by urban forests.

In addition, the critical role of UGSs in carbon sequestration, storing significant amounts of CO_2, has great potential for contributing to climate change mitigation. The economic valuation of these sequestration services informs the importance of investing in and maintaining UGS. While maintaining healthy trees is crucial to retain carbon stored, tree maintenance activities can contribute to carbon emissions that could offset some of the carbon gains. Carbon footprint analysis of UGSs, including associated maintenance activities, is recommended for future studies. Regarding local climate, although oxygen production by urban trees like *Q. acutissima* Carruth., *J. chinensis* L., and *L. tulipifera* L. has a minimal impact on overall atmospheric oxygen levels, it enhances their ecological value, particularly for local air quality.

Despite the negligible impact observed when considering the broader precipitation patterns of Daejeon and Yuseong-gu, the localized benefit remains significant. The strong correlation between leaf area and runoff reduction underscores the importance of species selection, tree health maintenance, and a healthy canopy cover. The monetized ESs can be viewed as avoided infrastructure costs and flood damage, highlighting the crucial role of urban trees in managing urban hydrology and enhancing water quality. Also, the high replacement value of urban trees such as *P. densiflora* Siebold & Zucc. and *P. rigida* Mill. in the study area shows the substantial financial investment required to replace their ecological services. The dominant contribution of pollution removal to the functional value of urban trees further explains their importance for their local environment.

Urban trees significantly reduce energy costs year-round through shading, evaporative cooling, wind blocking in summer, and their strategic planting and density effects in winter. The economic and ecological benefits provided by these urban trees, particularly in terms of pollution removal, runoff reduction, and carbon sequestration, justify the ongoing investment in urban forestry programs in the university. Enhancing these services through strategic tree management and planning can significantly improve the quality of urban life and the resilience of urban ecosystems.

This study is limited to a single year of meteorological and air quality data. Continuous long-term data would provide more comprehensive insights into ecosystem service provision. The i-Tree Eco model estimates air pollution removal using an average deposition velocity derived from tree coverage area, leaf area index, and hourly local air pollution data. For individual trees, the total pollutant removal is prorated based on the proportion of the total leaf area. It is important to note that the model does not account for the varying pollutant removal capabilities of different tree species, focusing solely on the leaf area attribute. Further research should address these limitations and explore the impact of different tree species on pollutant removal. Future studies, such as benefit–cost analyses, can be conducted to quantify and compare the economic benefits of urban green space investments against the costs of maintenance and management. Additionally, ecosystem services mapping is recommended to assess the potential of this tool for sustainable planning of green cities, considering methodological approaches, variety of data types, and the range of services assessed. Such analyses would aid in prioritizing investments, rationalizing funding allocations, and effectively communicating the value of urban trees to stakeholders and policymakers.

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