

## Article

# Ecosystem Services of the Historic Landscape Forest of Jinju Fortress, South Korea: A Species-Level Assessment Using i-Tree Eco

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## Abstract

Historic landscape forests within cultural heritage sites represent a distinct category of urban green space that provides critical ecosystem services under strict conservation constraints. This study applied i-Tree Eco v6.0 to quantify the ecosystem services of the historic landscape forest of Jinju Fortress (Jinjuseong; Historic Site No. 118), South Korea, with focus on species-level contributions. A total of 822 trees representing 30 species were inventoried across 1.272 ha of tree cover. *Zelkova serrata* was the dominant species (importance value = 57.8) and contributed disproportionately to all ecosystem service categories, accounting for 40.7% of air pollutant removal, 61.3% of carbon storage, 58.2% of carbon sequestration and oxygen production, and 55.4% of avoided runoff. The forest removed 123.1 kg yr<sup>−1</sup> of air pollutant Korean Won (KRW 8.834 million yr<sup>−1</sup>), stored 200.7 t (KRW 138 million), sequestered 8.834 t/yr (KRW 6.09 million/yr), produced 23.56 t/yr<sup>−1</sup> of oxygen, avoided 10,413.7 L yr<sup>−1</sup> of runoff and had a structural replacement value of KRW 1.63 billion. Beyond providing a species-level baseline for evidence-based management, this study introduces the concept of Heritage Ecosystem Service Efficiency (HESE) and the Species Ecosystem Service Dominance Index (SESDI), offering transferable frameworks for evaluating and managing ecosystem service performance in conservation-constrained heritage forests.

**Keywords:** i-Tree Eco; ecosystem services; Jinju Fortress; urban forest; air pollutant removal; carbon storage; carbon sequestration; oxygen production; avoided runoff; nature-based solutions



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## 1. Introduction

Urban forests and green spaces are increasingly recognized as cost-effective nature-based solutions for mitigating climate change, improving air quality, and enhancing urban liveability [1,2]. The Millennium Ecosystem Assessment (2005) [3] established the scientific basis for quantifying ecosystem services including air pollutant removal, carbon storage, oxygen production, and storm water regulation as measurable contributions of urban trees to human well-being. The magnitude of these services is strongly influenced by tree

structural attributes, particularly leaf area, species composition, and diameter distribution, as well as local environmental conditions [4,5]. Consequently, robust and standardized assessment frameworks are essential for quantifying ecosystem services and supporting evidence-based planning and management of urban forests.

To facilitate standardized quantification of ecosystem services, the United States Department of Agriculture Forest Service developed i-Tree Eco [6], an internationally validated model that integrates field-based tree measurements with meteorological and air quality data [7,8]. The model is currently applied in more than 100 countries [9,10] and has become one of the most widely adopted tools for evaluating the ecological and economic benefits of urban forests. In South Korea, i-Tree Eco has been adapted by the National Institute of Forest Science through the incorporation of domestic meteorological datasets, national air pollutant records, and species-specific allometric parameters for Korean tree taxa [11,12], enabling more reliable ecosystem service estimation under local environmental conditions.

The application of i-Tree Eco in South Korea has expanded considerably in recent years. For example, Ref. [13] evaluated the ecosystem services provided by street trees in Suwon City, and while Ref. [14] assessed 15 forest sites within the AiCAN network. Collectively, these studies demonstrate that species composition, stand structure, and tree size distribution are primary determinants of ecosystem service provision. More directly relevant to the present study, Ref. [15] applied i-Tree Eco to the Joseon Royal Tombs (Seolleung and Jeongneung), providing the first ecosystem service baseline for a heritage landscape forest in South Korea. Beyond Korea, ecosystem service assessments have increasingly been conducted in historic parks, temple forests, castle landscapes, and other culturally significant green spaces, highlighting the growing recognition of heritage forests as important providers of ecological, cultural, and socioeconomic benefits [16–23]. Nevertheless, these studies have primarily emphasized site-level ecosystem service valuation, while relatively few have examined the contribution of individual tree species within protected heritage landscapes.

Unlike conventional urban forests, which are generally managed to optimize ecosystem services, public recreation, and urban environmental quality, heritage forests exist within protected cultural landscapes where ecological management must be reconciled with the preservation of historical authenticity, archaeological resources, and cultural identity [16,17,23]. Management decisions are therefore governed not only by ecological considerations but also by legal protection frameworks, conservation guidelines, and restrictions on landscape alteration, often limiting interventions such as species replacement, thinning or large-scale planting. Moreover, the ecological value of heritage forests is strongly influenced by long-lived veteran trees that have accumulated substantial ecosystem service capacity over decades or centuries [15,17,18,23]. Consequently, these forests represent unique socio-ecological system in which ecosystem functions and cultural significance are intrinsically interconnected [20–22]. Although ecosystem service assessment frameworks such as i-Tree Eco provide robust estimates of carbon storage, air pollutant removal, runoff mitigation, and other ecosystem services, they were originally developed for conventional urban forests and therefore provide limited guidance for conservation decisions in protected heritage landscapes. Similarly, commonly used structural metrics, such as important value or dominance indices, effectively describe species composition and stand structure but do not quantify the relative contribution of individual tree species to ecosystem delivery. These limitations highlight the need for complementary assessment approaches that integrate species-level ecosystem service performance with the conservation priorities of heritage forests, thereby supporting more informed and evidence-based management decisions.

Despite recent advances in ecosystem service assessment, three important knowledge gaps remain. First, international evidence on ecosystem service assessment in historic landscape forest remains limited, with most studies focus on conventional urban forests, parks and street trees rather than culturally protected heritage landscapes. Consequently, the ecological functions, conservation values, and management implications of heritage forests remain insufficiently understood within a global context. Second, existing ecosystem service assessments primarily quantify ecosystem services at the stand or site level and rarely evaluate the relative contribution of individual tree species, limiting their usefulness for species-specific conservation and management decisions. Third, current assessments do not explicitly account for the unique conservation objectives, and management constraints associated with protected heritage landscapes, thereby limiting their applicability for balancing ecosystem service enhancement with cultural heritage preservation. To address these gaps, this study introduces two complementary indicators: the SESDI, which quantifies the relative contribution of individual tree species to ecosystem service provision, and the HESE index, which evaluates ecosystem service performance within the conservation context of heritage forests. Together, these indicators extend conventional i-Tree Eco assessments by linking species-level ecosystem service delivery with heritage conservation priorities, thereby providing a more comprehensive framework for evidence-based management of culturally significant forest landscapes.

Jinju Fortress (Jinjuseong; Historic Site No. 118), located in Jinju City, South Gyeongsang Province, South Korea, provides a compelling case for ecosystem service assessment in heritage landscape forests. As a nationally designated heritage site containing approximately 17.6 ha of landscape forest dominated by mature *Zelkova serrata*, the fortress is managed under conservation constraints that limit intensive interventions such as large-scale planting or thinning. Under these conditions, identifying high-performing species is essential for sustainable long-term management and conservation planning. Accordingly, this study applied i-Tree Eco v6.0 to: (1) characterize the forest structure and species composition of the Jinju Fortress landscape forest; (2) quantify annual air pollutant removal, carbon storage and sequestration, oxygen production, and avoided runoff at both site and species levels; (3) estimate the economic value of these ecosystem services using domestic valuation criteria; and (4) compare species-level performance with findings from previous Korean and international studies to identify species most critical for maintaining ecosystem service delivery within this historic landscape.

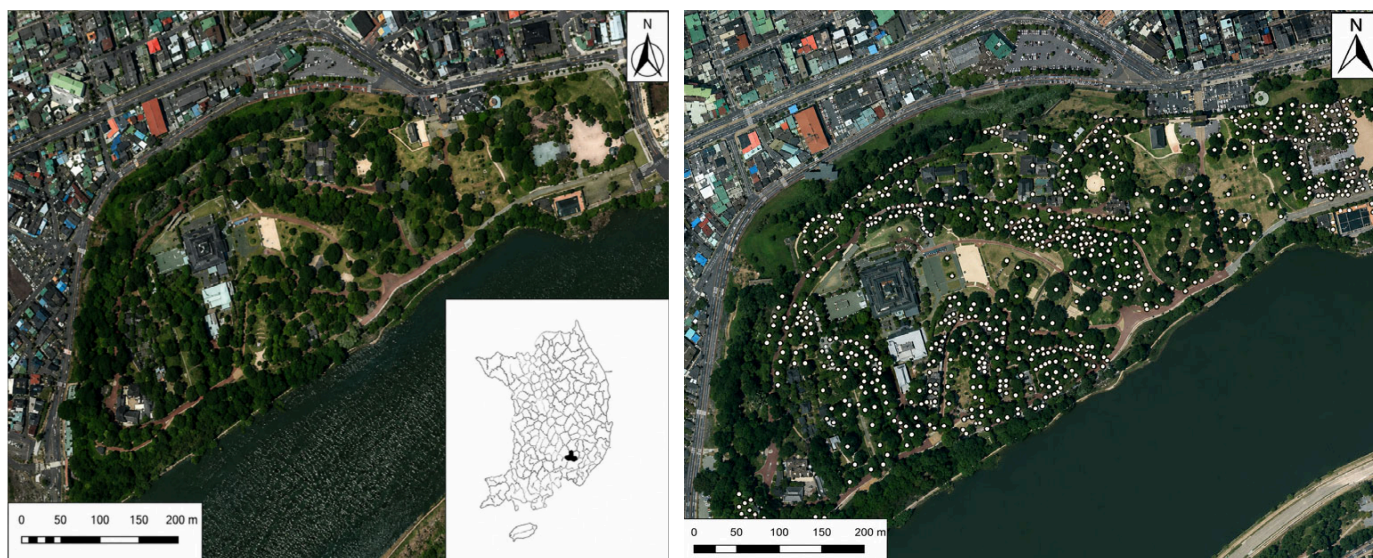
## 2. Materials and Methods

### 2.1. Study Site

Jinju Fortress (35°11' N, 128°05' E) is a nationally designated historic site (Historic Site No. 118) located in Jinju City, Gyeongnam Province, South Korea. The fortress covers a total area of 176,804 m<sup>2</sup> (approximately 17.6 ha) and is enclosed by a stone wall extending approximately 1.7 km, incorporating earthen embankments, sloped woodland areas, and open spaces adjacent to the Namgang (Nam River). The site has held military and political significance since the Goryeo period and is particularly renowned for the Siege of Jinju during the Japanese invasions of Korea (1592–1598). At present, Jinju Fortress functions not only as a nationally protected cultural heritage site, but also as a municipal landscape park, and an important regional ecological corridor, attracting approximately 1.5 million visitors annually.

The climate of Jinju is warm-temperate (Köppen: Cfa), with a mean annual temperature of approximately 14 °C and mean annual precipitation of 963 mm, most of which occurs during the June–September monsoon season. Vegetation within the fortress is dominated by broad-leaved deciduous species typical of the temperate forests of southern Korea,

distributed across embankment slopes, riparian margins along the Namgang, and developed park areas within the fortified perimeter. The forest canopy is primarily composed of *Zelkova serrata*, a species historically favored in Korean cultural landscape planting for its longevity, broad shade canopy, and cultural associations with communal gathering and continuity. Coniferous species, particularly *Pinus densiflora* are concentrated along the outer embankment slopes and perimeter zones adjacent to the stone wall (Figure 1).



**Figure 1.** Location and overview of the study site (Jinju Fortress, Jinju, South Korea). The map shows the spatial distribution of surveyed trees across the fortress area and the surrounding urban context.

## 2.2. Tree Inventory and Data Collection

A comprehensive field survey was conducted following the Korean i-Tree Eco protocol developed by Gwak [11], which standardizes tree measurement, data recording, and model parameterization Korean urban and landscape forests. This protocol has been widely in previous i-Tree Eco studies in Korea [13–15,24,25], ensuring methodological consistency and comparability among studies. The inventory employed a complete census approach rather than sample-based plots, whereby all live trees with a diameter at breast height (DBH)  $\geq 2.54$  cm (1 inch) located within the officially designed boundary of Jinju Fortress were surveyed. Shrubs and multi-stemmed woody plants below the minimum DBH threshold were excluded in accordance with the i-Tree Eco field protocol.

The study boundary was delineated using the official management map of Jinju Fortress (Historic Site No. 118) and verified through field reconnaissance prior to data collection to ensure complete spatial coverage of the heritage landscape forest. For each tree, species identity (scientific and Korean common names), DBH (cm), total tree height (m), crown width in four cardinal directions (m), crown base height (m), crown light exposure (CLE; classes 1–5), crown dieback (%), crown missing (%), and crown density (%) were recorded following the standardized procedures described in the i-Tree Eco Field Guide [6,11]. DBH was measured at 1.2 m above ground level on the uphill side of the stem, consistent with Korean forestry measurement standards [11]. Crown width measurements were subsequently used to estimate crown projection area and total leaf area using species-specific leaf area relationships embedded within the Korean i-Tree Eco database. Leaf area is a critical input variable governing dry deposition, rainfall interception, carbon sequestration, and BVOC emission calculations within the model [5,26].

To enhance measurement accuracy and ensure data reproducibility, a quality assurance and quality control (QA/QC) protocol was implemented throughout the inventory process. All field personnel received training in species identification, tree measurement techniques, and standardized data recording prior to fieldwork. Species identification followed the Korean National Standard Plant List and relevant regional floras, while trees with uncertain taxonomic identity or inconsistent measurements were independently re-examined by senior investigators. Approximately 10% of the inventory records were randomly selected for repeat measurement to assess measurement consistency and minimize observer bias. Following completion of the field survey, all records were independently reviewed for transcription errors, duplicate entries, missing values, and logical inconsistencies before being imported into the i-Tree Eco v6.0 database. Additional validation was performed within the i-Tree Eco data management interface to ensure that all required variables met the model's quality control criteria prior to ecosystem service estimation.

Meteorological and air quality data required by i-Tree Eco were obtained from official national monitoring networks. Hourly meteorological variables, including air temperature ( $^{\circ}\text{C}$ ), relative humidity (%), wind speed at canopy height ( $\text{m s}^{-1}$ ), solar radiation ( $\text{W m}^{-2}$ ), and precipitation (mm), were obtained from the Jinju Meteorological Observing operated by the Korea Meteorological Administration. Hourly concentrations of the six atmospheric pollutants used by i-Tree Eco ( $\text{O}_3$ ,  $\text{SO}_2$ ,  $\text{NO}_2$ ,  $\text{CO}$ ,  $\text{PM}_{10}$ , and  $\text{PM}_{2.5}$ ) were obtained from the nearest monitoring station of the National Air Pollutant Monitoring Network station. These datasets were synchronized with the field inventory and subsequently incorporated into the Korean implementation of i-Tree Eco v6.0 using localized parameter set developed by the National Institute of Forest Science [11]. The integrating of locally calibrated meteorological observations, air pollutant datasets, and species-specific allometric parameters improves the accuracy of ecosystem service estimation under Korean environmental conditions and ensures consistency with previous national applications of the model [11,13–17].

### 2.3. Korean i-Tree Eco v6.0 Model and Parameterization

Ecosystem services were quantified using the Korean implementation of i-Tree Eco v6.0 (USDA Forest Service, Washington, DC, USA), a process-based urban forest assessment model that integrates field-measured tree characteristics with meteorological, air quality and species-specific physiological data to estimate the ecological and economic benefits of urban trees [6,9]. The model has been extensively validated and applied internationally for assessing ecosystem services such as air pollutant removal, carbon storage and sequestration, oxygen production, avoided runoff, structural value, and BVOC emissions [5,6,9,26].

To improve estimate accuracy under Korean environmental conditions, the National Institute of Forest Science (NIFoS) developed a localized parameter set by incorporating nationally calibrated datasets into the standard i-Tree Eco framework [11]. Compared with the original U.S. version, the Korean implementation utilizes meteorological observations from the Korean Meteorological Administration, national ambient air pollutant datasets, locally calibrated precipitation records, and species-specific allometric equations for major Korean tree species. These localized datasets more accurately represent regional climatic conditions, atmospheric pollution characteristics, and tree growth patterns, thereby reducing uncertainty associated with transferring default model parameters developed for different ecological regions [4,11].

Tree biomass and carbon storage were estimated using species-specific allometric equations embedded within the Korean i-Tree Eco database whenever available. For species lacking local allometric relationships, the model automatically applies taxonomically appropriate equations following the hierarchical parameter selection procedure implemented in i-Tree Eco [6,26]. Carbon content was assumed to represent 50% of aboveground dry

biomass, and an open-grown adjustment factor of 0.8 was applied to account for the lower wood density and branching architecture typically observed in urban trees relative to closed-forest stands [27–29].

Air pollutant removal calculations incorporated hourly concentrations of ozone (O<sub>3</sub>), sulfur dioxide (SO<sub>2</sub>), nitrogen oxide (NO<sub>2</sub>), carbon monoxide (CO), particulate matter less than 10 µm (PM<sub>10</sub>), and particulate matter less than 2.5 µm (PM<sub>2.5</sub>), together with hourly meteorological variables controlling dry deposition processes. Pollutant deposition velocities were calculated dynamically according to atmospheric resistance theory using species characteristics, canopy structure, leaf phenology, and prevailing meteorological conditions [5,26,30]. Hydrological processes, including rainfall interception and avoided surface runoff, were estimated using canopy storage capacity and leaf area index, while BVOC emissions were simulated from species-specific emission factors, leaf biomass, air temperature, photosynthetically active radiation following the standard i-Tree Eco algorithms [5,26].

The Korean implementation also incorporates domestic economic valuation coefficients for carbon sequestration, air pollutant removal, structural replacement value, and other ecosystem services, allowing all ecological benefits to be expressed in Korean Won (KRW) using nationally relevant valuation criteria [11]. Employing these localized parameters ensures methodological consistency with previous Korean i-Tree Eco studies [13–15] while improving the reliability and comparability of ecosystem service estimates for Korean heritage forests. The principal calculation methods and equations used by i-Tree Eco v6.0 for each ecosystem service category are summarized in Table 1. All model simulations were performed using identical parameter settings and standardized input datasets to ensure the reproducibility and comparability of the ecosystem service estimates generated in this study.

**Table 1.** Summary of i-Tree Eco v6.0 calculation methods for each ecosystem service category.

| Ecosystem Service     | Formula/Principle                                                   | Key Parameters                                                                                             |
|-----------------------|---------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Air pollutant removal | $F = C \times Vd$<br>$Vd = 1/(Ra + Rb + Rc)$                        | C: pollutant conc. (µg/m <sup>3</sup> )<br>Vd: deposition velocity (m/s)<br>Ra, Rb, Rc: resistances [5,30] |
| Carbon storage        | Biomass $\times$ 0.5 $\times$ 0.8<br>(allometric equations)         | Species allometric eq.<br>C fraction = 0.5<br>Open-grown factor = 0.8 [27–29]                              |
| Carbon sequestration  | $\Delta C$ storage yr <sup>−1</sup><br>(adjusted for decomposition) | Annual DBH increment<br>Biomass equations [29]                                                             |
| Oxygen production     | $O_2 = \text{net C seq.} \times (32/12)$                            | Net C sequestration (kg/yr)<br>Molar mass ratio O <sub>2</sub> :C [31]                                     |
| Avoided runoff        | $I_{max} = SL \times LAI$<br>Annual interception integration        | SL = 0.2 mm per event<br>LAI per tree<br>Precipitation records [5]                                         |
| Replacement value     | $V = P \times A \times S \times C \times L$<br>(CTLA trunk formula) | P: base unit price<br>A, S, C, L: correction factors [11]                                                  |
| VOC emissions         | $E = BER \times \text{leaf biomass} \times f(T, PAR)$               | Species base emission rates<br>Temperature, PAR [5,26]                                                     |

Annual oxygen production was derived from net carbon sequestration using the stoichiometric relationship: O<sub>2</sub> production = net C sequestration  $\times$  (32/12) [11], corresponding to the net photosynthetic exchange of CO<sub>2</sub> for O<sub>2</sub> over the growing season.

Avoided runoff was estimated using a canopy interception model in which maximum storage capacity per precipitation event ( $I_{\max}$ ) is calculated as  $I_{\max} = SL \times LAI$ , where  $SL$  is the species-specific leaf storage capacity (0.2 mm per unit leaf area) and  $LAI$  is the leaf area index of each tree. Annual avoided runoff represents the cumulative volume of precipitation intercepted by the canopy and returned to the atmosphere through evaporation rather than reaching the ground surface, integrated over all rainfall events during the growing season [5]. Structural replacement value was estimated using the Council of Tree and Landscape Appraisers (CTLA) trunk formula method ( $V = P \times A \times S \times C \times L$ ), in which  $P$  is the base unit price per unit trunk cross-sectional area, and  $A$ ,  $S$ ,  $C$ , and  $L$  are correction factors for species appraisal, site condition, tree condition, and location, respectively [11]. Economic values for all service categories were calculated using the unit prices incorporated in the Korean i-Tree Eco parameter set [11].

#### 2.4. Ecosystem Service Estimation

The ecosystem services provided by the Jinju Fortress landscape forest were quantified using the Korean implementation of i-Tree Eco v6.0 following the standardized calculation procedures embedded within the model [5,6,9,26]. Based on the field inventory and localized meteorological and air quality datasets described above, the model estimated ecosystem services at the individual tree, species, and site levels. The assessed ecosystem services included air pollutant removal, carbon storage, annual carbon sequestration, oxygen production, avoided runoff, structural replacement value, and BVOC emissions. Economic values were calculated using the Korean valuation coefficients incorporated into the localized i-Tree Eco parameter set [11].

Air pollutant removal was estimated using the dry deposition resistance approach, carbon storage and sequestration were calculated from species-specific allometric biomass equations, oxygen production was derived from annual carbon sequestration based on photosynthetic stoichiometry, avoided runoff was estimated using the canopy rainfall interception model, structural replacement value was determined using the Council of Tree and Landscape Appraisers (CTLA) trunk formula, and BVOC emissions were estimated from species-specific emission factors together with leaf biomass and meteorological conditions (Table 1). The ecosystem service outputs generated in this section were subsequently used to develop the Species Ecosystem Service Dominance Index (SES DI) and the HESE index.

The SES DI and HESE index were developed as composite indicators to evaluate the diversity and efficiency of Heritage Ecosystem Services (HES). SES DI integrates species diversity with structural importance by combining species richness, diversity metrics, and the normalized Importance Value (NIV) of each species to quantify the capacity of heritage ecosystems to sustain multiple ecosystem services. HESE was developed to assess the efficiency with which Heritage Ecosystem Services are generated relative to management inputs and environmental pressures. The index was computed as the weighted ratio of standardized ecosystem service outputs including provisioning, regulating, supporting, and cultural services to standardized management and ecological input variables. Prior to aggregation, all indicators were normalized to a common scale, and weighting coefficients were assigned using an appropriate weighting approach, such as equal weighting, the Analytic Hierarchy Process (AHP), or entropy weighting. Higher SES DI values indicate greater ecosystem service diversity supported by structurally important species, whereas higher HESE values reflect more efficient provision of Heritage Ecosystem Services under comparable environmental and management conditions.

### 3. Results

#### 3.1. Forest Structure and Species Composition

A total of 822 trees representing 44 species were inventoried within the study area. Total tree cover was 1.272 ha, corresponding to a total leaf area of 9.271 ha and a leaf area index (LAI) of approximately 7.3 across the canopied zone. This tree cover of 1.272 ha represents approximately 7.2% of the total fortress area (17.6 ha). The total structural replacement value, estimated using the CTLA trunk formula method, was KRW 1.63 billion (approximately USD 1.22 million).

Analysis of species composition by importance value (IV), calculated as the mean of relative population percentage and relative leaf area percentage, identified *Zelkova serrata* as the overwhelmingly dominant species (IV = 57.8). This was followed by *Prunus × yedoensis* (IV = 9.2), *Pinus densiflora* (IV = 7.8), and *Celtis sinensis* (IV = 5.3), whereas remaining 26 species collectively accounted for comparatively minor combined IV of 19.9 (Table 2).

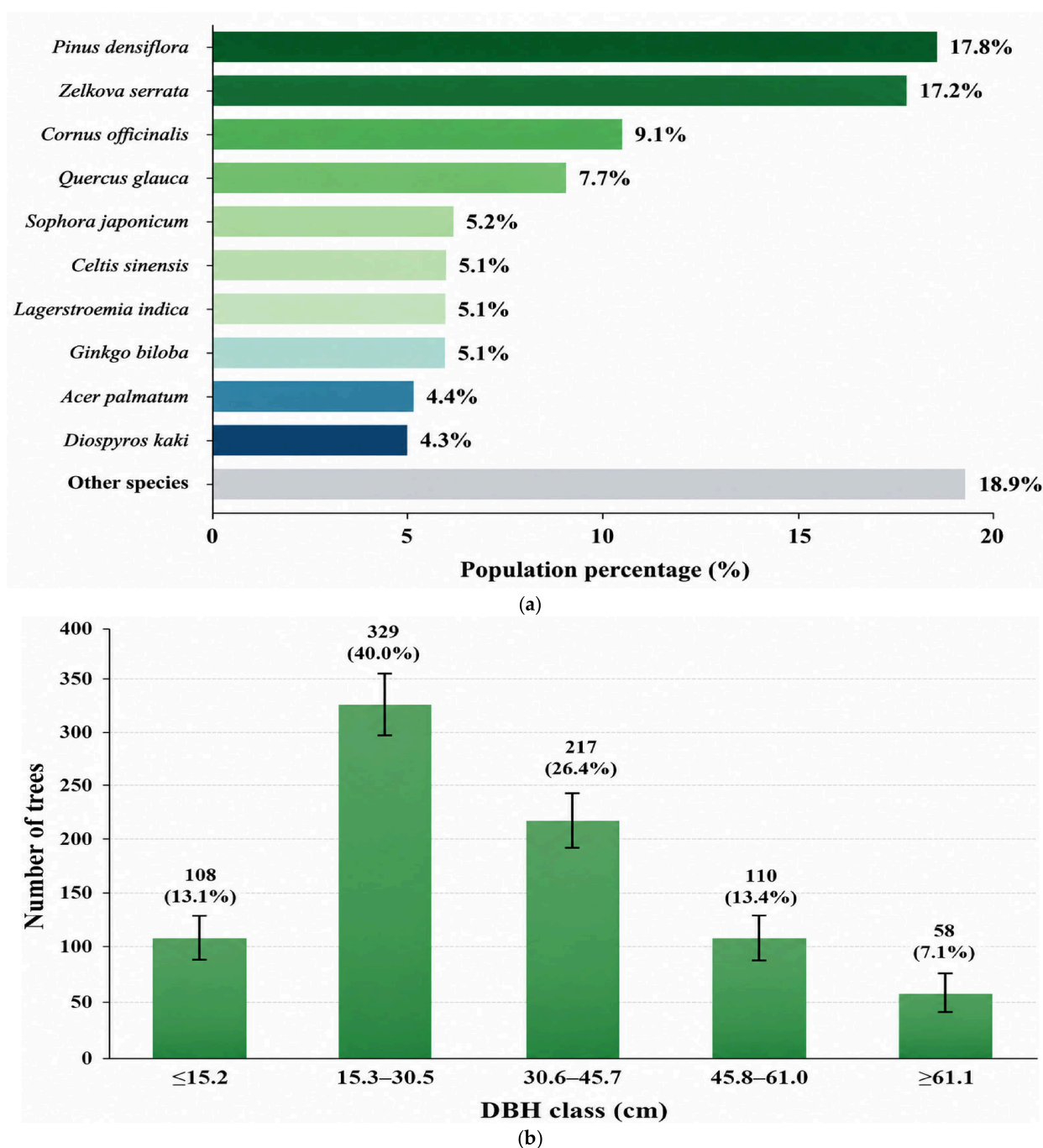
**Table 2.** Importance value (IV), population proportion (%), and leaf area proportion (%) by tree species at Jinju Fortress.

| Species                        | N   | Population (%) | Leaf Area (%) | IV    |
|--------------------------------|-----|----------------|---------------|-------|
| <i>Zelkova serrata</i>         | 141 | 17.2           | 40.7          | 57.8  |
| <i>Pinus densiflora</i>        | 146 | 17.8           | 5.9           | 23.7  |
| <i>Quercus glauca</i>          | 63  | 7.7            | 10.7          | 18.4  |
| <i>Celtis sinensis</i>         | 42  | 5.1            | 11.8          | 16.9  |
| <i>Ginkgo biloba</i>           | 42  | 5.1            | 7.0           | 12.1  |
| <i>Cornus officinalis</i>      | 75  | 9.1            | 0.8           | 9.9   |
| <i>Styphnolobium japonicum</i> | 43  | 5.2            | 3.1           | 8.4   |
| <i>Quercus myrsinifolia</i>    | 23  | 2.8            | 5.0           | 7.8   |
| <i>Chionanthus retusus</i>     | 27  | 3.3            | 2.7           | 6.0   |
| <i>Lagerstroemia indica</i>    | 42  | 5.1            | 0.7           | 5.8   |
| Other species (20 spp.)        | 178 | 21.6           | 11.6          | 33.2  |
| Total                          | 822 | 100.0          | 100.0         | 200.0 |

The strong numerical and structural dominance of *Z. serrata*, a species widely planted in Korean historic parks, fortress landscapes, and traditional public spaces, for its longevity, and expansive shade canopy, resulted in highly uneven species importance distribution. The relatively high IV of *P. densiflora* compared with its population share reflects its characteristically large canopy size and its evergreen foliage, which contribute disproportionately to the site-level leaf area index throughout the year despite its comparatively lower abundance.

DBH class distribution revealed a mature, adult-dominant forest structure, with the largest proportion of trees (approximately 47.3%) concentrated in the 15.3–30.5 cm DBH class. Trees in the  $\geq 61.1$  cm DBH category represented approximately 8.6% of the total population, yet contributed disproportionately to carbon storage and structural replacement value because of their substantially greater individual biomass. Sensitivity analysis of i-Tree Eco have identified DBH as the most influential input parameter affecting estimates of both carbon storage and annual carbon sequestration [14], underscoring the ecological significance of this large-diameter cohort.

In contrast, the smallest DBH class ( $\leq 15.2$  cm) comprised approximately 13.1% of total tree population, indicating limited recent canopy recruitment (Figure 2). This pattern is consistent with the intensive management practices typical of heritage landscapes, where understory regeneration is often intentionally suppressed through routine ground management.



**Figure 2.** (a) Species composition by importance value (IV) at Jinju Fortress. (b) DBH class distribution (cm) of all 822 surveyed trees.

### 3.2. Ecosystem Services

#### 3.2.1. Air Pollutant Removal

The 822 inventoried trees removed a total of 123,058.6 g (123.1 kg) of air pollutants annually from the atmosphere, with a combined economic value of KRW 8.31 million/yr. Pollutant removal, ranked by total mass removed, followed the order:  $PM_{10}^* > O_3 > SO_2 > NO_2 > CO > PM_{2.5}$ . Annual pollutant removal averaged 96.8 kg/ha/yr of tree cover, while mean removal per tree was estimated at 0.150 kg/tree/yr (Table 3).

**Table 3.** Annual air pollutant removal (g/yr) and economic value (KRW/yr) by tree species at Jinju Fortress.

| Species                | O <sub>3</sub> (g/yr) | SO <sub>2</sub> (g/yr) | NO <sub>2</sub> (g/yr) | CO (g/yr) | PM <sub>10</sub> (g/yr) | PM <sub>2.5</sub> (g/yr) | Total (g/yr) | Ratio (%) |
|------------------------|-----------------------|------------------------|------------------------|-----------|-------------------------|--------------------------|--------------|-----------|
| <i>Z. serrata</i>      | 27,583.2              | 3579.2                 | 5999.1                 | 659.0     | 11,151.9                | 1081.4                   | 50,053.8     | 40.7      |
| <i>C. sinensis</i>     | 8001.8                | 1038.1                 | 1740.4                 | 191.0     | 3235.3                  | 314.2                    | 14,520.8     | 11.8      |
| <i>Q. glauca</i>       | 7281.3                | 945.0                  | 1583.3                 | 174.1     | 2944.1                  | 285.9                    | 13,213.7     | 10.7      |
| <i>G. biloba</i>       | 4722.8                | 612.5                  | 1027.0                 | 112.6     | 1909.5                  | 185.4                    | 8569.8       | 7.0       |
| <i>P. densiflora</i>   | 4033.4                | 523.2                  | 876.6                  | 96.7      | 1630.0                  | 158.0                    | 7317.9       | 5.9       |
| <i>Q. myrsinifolia</i> | 3360.2                | 436.0                  | 730.9                  | 80.2      | 1358.6                  | 131.9                    | 6097.8       | 5.0       |
| <i>S. japonicum</i>    | 2125.8                | 275.8                  | 462.3                  | 50.8      | 859.7                   | 83.5                     | 3857.9       | 3.1       |
| <i>C. retusus</i>      | 1812.4                | 235.1                  | 393.9                  | 43.6      | 732.8                   | 71.2                     | 3289.0       | 2.7       |
| <i>P. koraiensis</i>   | 1574.7                | 204.3                  | 342.2                  | 37.7      | 636.7                   | 61.7                     | 2857.3       | 2.3       |
| <i>A. holophylla</i>   | 996.3                 | 129.3                  | 216.6                  | 23.9      | 402.8                   | 39.3                     | 1808.2       | 1.5       |
| Other species          | 12,065.5              | 1568.7                 | 2628.4                 | 287.4     | 4888.4                  | 474.8                    | 21,913.2     | 17.8      |
| Total                  | 73,557.4              | 9546.2                 | 15,000.7               | 1756.0    | 29,749.8                | 2887.3                   | 123,058.6    | 100.0     |

At the species level, *Z. serrata* accounted for the largest proportion of total air pollutant removal across the site (40.7%), followed by *Prunus × yedoensis* (12.4%) and *P. densiflora* (10.1%). These contributions reflect both the numerical dominance of *Z. serrata* and its comparatively large individual leaf area. The contribution of *P. densiflora* is particularly notable relative to its (IV 23). As an evergreen species, it maintains year-round dry deposition activity during winter months when deciduous species are leafless, thereby increasing its effective annual deposition capacity beyond what would be based solely on population share. Similar patterns have been documented in conifer-dominated urban forests in both Korean and international contexts [14,30,32].

Comparison with previous Korean i-Tree Eco studies highlights the characteristic ecosystem service profile of a small, mature, deciduous-dominated heritage forest. A study by [15] reported a total annual pollutant removal of 5400 kg/yr from 10,643 trees at the Joseon Royal Tombs (Seolleung and Jeongneung), equivalent to approximately 0.51 kg/tree/yr, substantially higher than the value observed at Jinju Fortress (0.150 kg/tree/yr). This difference is partly attributable in part to the greater proportion of coniferous species at the Royal Tombs, which maintain year-round pollutant deposition. Similarly, a study by [13] estimated 7930 kg/yr of pollutant removal from 43,124 street trees in Suwon (0.184 kg/tree/yr), while another study by [26] documented 131 kg/yr from 287 trees at Chungnam National University (0.457 kg/tree/yr), reflecting relatively favorable deposition conditions at that site.

The annual pollutant removal rate at Jinju Fortress (96.8 kg/ha/yr) was also notably lower than the highest-performing AiCAN sites documented by [14], where Ulsan recorded 504.61 kg/ha/yr. Internationally, urban trees in Tehran were estimated to remove 1286.4 t/yr of pollutants [33]; however, this represented only 0.17% of total city emissions, illustrating the broader principle that absolute pollutant removal is constrained by canopy extent and that species composition strongly influences removal efficiency on a per-unit area basis [32]. The comparatively lower per-hectare removal efficiency at Jinju Fortress is primarily associated with the limited proportion of evergreen species within the canopy, suggesting that selective integration of native evergreen broad-leaved species could enhance year-round pollutant removal capacity while maintaining the ecological and cultural integrity of the heritage landscape.

### 3.2.2. Carbon Storage and Sequestration

Total carbon storage across the 822 inventoried trees was estimated at 200,711.4 kg (200.7 t), with an associated economic value of approximately KRW 138 million. Annual net carbon sequestration was estimated at 8834.2 kg/yr (8.834 t/yr), corresponding to an annual economic value of KRW 6.09 million. On a per-unit area basis, values were 157.8 t/ha for storage and 6.94 t/ha/yr for annual sequestration; per-tree averages were 244.2 kg/tree for stored carbon and 10.75 kg/tree/yr for annual sequestration.

*Z. serrata* dominated both carbon storage (61.3% of site total) and annual sequestration (58.2%), consistent with its high importance value and its characteristically dense, long-lived hardwood producing substantial annual wood increment. *P. densiflora* contributed a further 13.7% of stored carbon, reflecting the considerable biomass accumulated in specimen trees of this species along the embankment slopes. *Celtis sinensis* and *Prunus × yedoensis* together accounted for approximately 12.0% of total stored carbon, with their contributions largely proportional to their respective leaf area shares.

The annual carbon sequestration rate per tree at Jinju Fortress (10.75 kg/tree/yr) exceeded those reported in comparable Korean i-Tree Eco studies (Table 4). For instance, a study by [15] reported 9.23 kg/tree/yr at the Joseon Royal Tombs; while Refs. [24,25] reported 7.19 kg/tree/yr for a university campus forest and 6.13 kg/tree/yr at Chungnam National University; while Ref. [13] reported 6.93 kg/tree/yr for Suwon street trees. The superior per-tree sequestration performance at Jinju Fortress is primarily attributable to the large mean DBH of the dominant *Z. serrata* population. As demonstrated by [26], DBH is the most influential variable affecting carbon storage and sequestration estimates in the i-Tree Eco model.

**Table 4.** Carbon storage (kg) and annual carbon sequestration (kg/yr) by tree species at Jinju Fortress.

| Species                | C Storage (kg) | Ratio (%) | C Seq. (kg/yr) | Ratio (%) | Seq./Tree (kg/yr) |
|------------------------|----------------|-----------|----------------|-----------|-------------------|
| <i>Z. serrata</i>      | 66,223.1       | 33.0      | 2234.7         | 25.3      | 15.85             |
| <i>Q. glauca</i>       | 32,970.1       | 16.4      | 1376.2         | 15.6      | 21.84             |
| <i>S. japonicum</i>    | 14,883.1       | 7.4       | 996.3          | 11.3      | 23.17             |
| <i>P.s densiflora</i>  | 14,360.0       | 7.2       | 950.9          | 10.8      | 6.51              |
| <i>Q. myrsinifolia</i> | 12,796.6       | 6.4       | 354.6          | 4.0       | 15.42             |
| <i>G. biloba</i>       | 12,197.9       | 6.1       | 316.1          | 3.6       | 7.53              |
| <i>A. palmatum</i>     | 5639.6         | 2.8       | 223.1          | 2.5       | 6.20              |
| <i>C. sinensis</i>     | 4734.0         | 2.4       | 153.3          | 1.7       | 3.65              |
| <i>C. retusus</i>      | 4639.7         | 2.3       | 349.2          | 4.0       | 12.93             |
| <i>U. parvifolia</i>   | 3845.2         | 1.9       | 237.9          | 2.7       | 33.99             |
| Other species          | 28,322.1       | 14.1      | 1642.9         | 18.6      | 8.56              |
| Total                  | 200,711.4      | 100.0     | 8834.2         | 100.0     | 10.75             |

This pattern is consistent with findings from Ho Chi Minh City, where older and larger trees in Tao Dan Park stored 1337 t of carbon and generated annual ecosystem service benefits values at USD 17,639/yr, nearly 3.5 times those of the younger-tree-dominated 23/9 Park (USD 5121/yr) [34]. In contrast, the annual carbon sequestration rate at Jinju Fortress on an area basis (6.94 t/ha/yr) was lower than that reported for the highest-performing AiCAN site, documented by [14] which was (6.94 t/ha/yr), largely because of the lower tree density characteristic of heritage landscape forests. Similarly, the site recorded lower per-hectare sequestration than urban forests in Luohe City, China [35], where tree densities were substantially higher across multiple green space types.

The contrast between high per-tree sequestration and moderate per-hectare performance reflects a fundamental trade-off in heritage forest management. These findings suggest that conserving existing mature trees can provide greater climate-mitigation ben-

efits on a per-tree basis than establishing large numbers of young trees at higher densities, emphasizing the ecological value of preserving large specimens within protected cultural landscapes.

#### SESDI and HESE

The results further suggest the potential utility of a Species Ecosystem Service Dominance Index (SESDI), defined as the ratio between a species' proportional ecosystem service contribution and its proportional representation within the tree population. Species with SESDI values greater than one contribute disproportionately to ecosystem service delivery relative to their abundance, whereas values below one indicate lower functional contribution. For example, *Z. serrata* represented only 17.2% of the tree population but contributed more than 40% of air pollutant removal and over 58% of carbon sequestration, indicating exceptionally high ecosystem service dominance. Future studies may apply SESDI to identify priority conservation species within urban and heritage forest ecosystems.

Unlike traditional importance value metrics that primarily describe structural dominance, SESDI explicitly links species abundance with ecosystem service contribution. As a result, SESDI can identify species that deliver disproportionately high ecosystem benefits despite relatively low abundance. This distinction may assist managers in prioritizing conservation actions, species selection and restoration planning in both urban and heritage forest ecosystems.

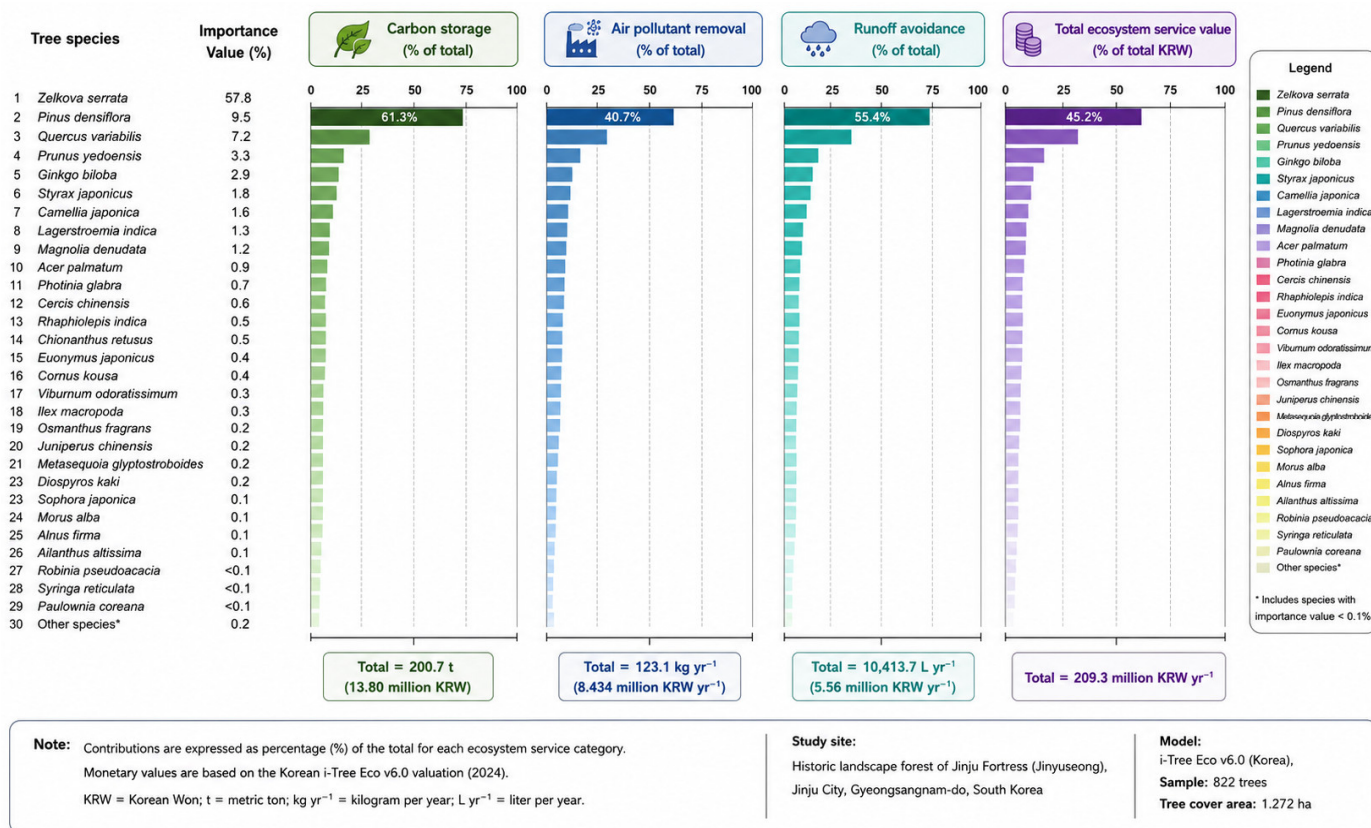
Table 5 demonstrates clear interspecific variation in ecosystem service performance among the dominant tree species of Jinju Fortress heritage forest. *Z. serrata* recorded the highest SESDI (0.330), confirming its dominant contribution across all ecosystem service categories and highlighting its critical role in sustaining the ecological functions of the heritage landscape. Although *Q. glauca* and *P. densiflora* ranked second and third in overall ecosystem service dominance, *J. japonicum* exhibited the highest HESE (0.857), indicating greater ecosystem service providers, whereas HESE reveals species with comparatively higher functional efficiency, offering complementary metrics for evidence based conservation prioritization and sustainable heritage forest management. The ecological significance and management implications of SESDI and HESE are discussed in Section 4.2.

**Table 5.** Interspecific variation in ecosystem service performance among the dominant tree species.

| Species                | IV   | Air Pollutant Removal (%) | Carbon Storage (%) | C. Sequestration (%) | Oxygen Production (%) | Avoided Runoff (%) | SESDI | HESE  | Rank |
|------------------------|------|---------------------------|--------------------|----------------------|-----------------------|--------------------|-------|-------|------|
| <i>Z. serrata</i>      | 57.8 | 40.7                      | 33.0               | 25.3                 | 25.3                  | 40.7               | 0.330 | 0.571 | 1    |
| <i>Q. glauca</i>       | 18.4 | 10.7                      | 16.4               | 15.6                 | 15.6                  | 10.7               | 0.138 | 0.750 | 2    |
| <i>P. densiflora</i>   | 23.7 | 5.9                       | 7.2                | 10.8                 | 10.8                  | 5.9                | 0.081 | 0.342 | 3    |
| <i>S. japonicum</i>    | 8.4  | 3.1                       | 7.4                | 11.3                 | 11.3                  | 3.1                | 0.072 | 0.857 | 4    |
| <i>C. sinensis</i>     | 16.9 | 11.8                      | 2.4                | 1.7                  | 1.7                   | 11.8               | 0.059 | 0.349 | 5    |
| <i>G. biloba</i>       | 12.1 | 7.0                       | 6.1                | 3.6                  | 3.6                   | 7.0                | 0.055 | 0.455 | 6    |
| <i>Q. myrsinifolia</i> | 7.8  | 5.0                       | 6.4                | 1.4                  | 1.4                   | 5.0                | 0.038 | 0.493 | 7    |
| <i>C. retusus</i>      | 6.0  | 2.7                       | 2.3                | 4.0                  | 4.0                   | 2.7                | 0.031 | 0.517 | 8    |
| <i>A. palmatum</i>     | 5.8  | 1.4                       | 2.8                | 2.5                  | 2.5                   | 1.4                | 0.021 | 0.366 | 9    |
| <i>C. officinalis</i>  | 9.9  | 0.8                       | 1.1                | 4.0                  | 4.0                   | 0.8                | 0.021 | 0.212 | 10   |

Figure 3 illustrates the species-level contributions to four major ecosystem service categories in the Jinju Fortress heritage forest. *Z. serrata* consistently dominated ecosystem service provision, contributing 61.3% of total carbon storage, 40.7% of air pollutant removal, 55.4% of avoided runoff, and 45.2% of the total ecosystem service value (KRW 209.3 million). The next highest contributors were *P. densiflora*, *Q. glauca*, *P. yedoensis*, and *G. biloba*, although each contributed substantially less than *Z. serrata*. Species with lower importance values provided comparatively minor ecosystem services. These results demonstrate that

ecosystem service provision is highly concentrated among few mature, dominant species, with *Z. serrata* functioning as the principle ecological asset within the heritage forest.



**Figure 3.** Proportional contribution of tree species to total ecosystem services.

### 3.2.3. Oxygen Production

Annual oxygen production was 23,560.0 kg/yr (23.56 t/yr), calculated from net carbon sequestration using the stoichiometric conversion factor of 32/12 [31], which represents the molar mass ratio of O<sub>2</sub> to C in the net photosynthetic process. Mean oxygen production per tree was 28.7 kg/tree/yr. *Z. serrata* accounted for 58.2% of total oxygen production, reflecting its dominant contribution to annual carbon sequestration. This relationship is expected because oxygen production and carbon sequestration are derived from the same net photosynthetic flux and are therefore mathematically linked through a constant stoichiometric conversion factor.

The annual oxygen production per tree at Jinju Fortress (28.7 kg/tree/yr) was substantially higher than values reported in comparable Korean i-Tree Eco studies (Table 6). A finding from [25] reported 19.14 kg/tree/yr for a university campus forest (7.37 t/yr total, 385 trees), while [26,36] reported 18.48 kg/tree/yr for Suwon street trees (796.9 t/yr total, 43,124 trees), and 8.43 kg/tree/yr at Chungnam National University (2.42 t/yr total, 287 trees), respectively. The superior per-tree oxygen production observed at Jinju Fortress is primarily attributable to the mature stature and large canopy dimensions of the dominant *Z. serrata* population, which support higher rates of photosynthetic carbon fixation, and which consequently results in greater oxygen production.

These figures highlight the disproportionate ecological contribution of large, mature heritage trees to atmospheric oxygen generation. They further emphasize the importance of conserving mature specimens within historic landscape forests, as mature trees generally provide substantially greater oxygen production per individual than younger, smaller trees.

**Table 6.** Annual oxygen production (kg/yr) by tree species at Jinju Fortress.

| Species                        | O <sub>2</sub> Production (kg/yr) | Ratio (%) | O <sub>2</sub> per Tree (kg/tree/yr) |
|--------------------------------|-----------------------------------|-----------|--------------------------------------|
| <i>Zelkova serrata</i>         | 5960                              | 25.3      | 42.27                                |
| <i>Quercus glauca</i>          | 3670                              | 15.6      | 58.25                                |
| <i>Styphnolobium japonicum</i> | 2660                              | 11.3      | 61.86                                |
| <i>Pinus densiflora</i>        | 2530                              | 10.7      | 17.33                                |
| <i>Cornus officinalis</i>      | 950                               | 4.0       | 12.67                                |
| <i>Chionanthus retusus</i>     | 930                               | 3.9       | 34.44                                |
| <i>Ginkgo biloba</i>           | 840                               | 3.6       | 20.00                                |
| <i>Lagerstroemia indica</i>    | 830                               | 3.5       | 19.76                                |
| <i>Ulmus parvifolia</i>        | 630                               | 2.7       | 90.00                                |
| <i>Acer palmatum</i>           | 590                               | 2.5       | 16.39                                |
| Other species                  | 3970                              | 16.9      | 19.85                                |
| Total                          | 23,560                            | 100.0     | 28.66                                |

### 3.2.4. Avoided Runoff

Annual avoided runoff was estimated at 10,413.7 L/yr (10.41 m<sup>3</sup>/yr), corresponding to an economic value of approximately KRW 29,300 per year (Table 7). Average canopy interception was 12.7 L/tree/yr. *Zelkova serrata* contributed approximately 55.4% of total avoided runoff, reflecting its dominance share of the site's total leaf area and canopy cover.

**Table 7.** Annual avoided runoff (L/yr) and economic value (KRW/yr) by tree species at Jinju Fortress.

| Species                        | Avoided Runoff (L/yr) | Ratio (%) | Per Tree (L/tree/yr) |
|--------------------------------|-----------------------|-----------|----------------------|
| <i>Zelkova serrata</i>         | 4235.8                | 40.7      | 30.04                |
| <i>Celtis sinensis</i>         | 1229.0                | 11.8      | 29.26                |
| <i>Quercus glauca</i>          | 1118.2                | 10.7      | 17.75                |
| <i>Ginkgo biloba</i>           | 725.3                 | 7.0       | 17.27                |
| <i>Pinus densiflora</i>        | 618.9                 | 5.9       | 4.24                 |
| <i>Quercus myrsinifolia</i>    | 516.1                 | 5.0       | 22.44                |
| <i>Styphnolobium japonicum</i> | 326.6                 | 3.1       | 7.60                 |
| <i>Chionanthus retusus</i>     | 278.1                 | 2.7       | 10.30                |
| <i>Pinus koraiensis</i>        | 241.7                 | 2.3       | 8.95                 |
| <i>Abies holophylla</i>        | 153.0                 | 1.5       | 10.20                |
| Other species                  | 971.0                 | 9.3       | 5.03                 |
| Total                          | 10,413.7              | 100.0     | 12.67                |

The total avoided runoff at Jinju Fortress (10.41 m<sup>3</sup>/yr) was modest compared with values reported for sites with larger canopy extent and leaf area. Similar studies [24] reported 203 m<sup>3</sup>/yr of avoided runoff from a 10.25 ha university campus green space, while Ref. [35] reported 122,637 m<sup>3</sup>/yr across the urban green space network of Luohe City in China. Moreover, Ref. [14] documented avoided runoff rates of up to 783.33 m<sup>3</sup>/ha/yr at the highest-performing AiCAN site in Ulsan. These differences largely reflect variation in canopy cover, total leaf area, and annual precipitation.

Within the heritage landscape context of Jinju Fortress, however, the significance of canopy interception extends beyond the total volume of runoff avoided. The fortress contains historic earthen embankments and stone walls that are particularly vulnerable to surface erosion during intense monsoon rainfall events. Large-canopy trees, especially *Z. serrata* individuals located along embankment margins, help intercept rainfall, reduce peak runoff intensity, and minimize direct soil exposure. Consequently, the forest canopy contributes not only to hydrological regulation but also to physical preservation of heritage structures.

This protective function is not reflected in the estimated monetary value of KRW 29,300/yr and therefore represents an additional ecosystem service unique to heritage landscapes. As such, the conservation of mature canopy trees can be justified not only on ecological grounds but also as an integral component of cultural heritage preservation. Similar conclusions have been reported in heritage-adjacent urban environments. For example, Ref. [35] estimated stormwater runoff reduction benefits of US\$3.26/tree/yr, for street trees in the Kyoto, demonstrating the broader economic and functional importance of this system service in culturally significant urban landscapes.

### 3.2.5. Biogenic Volatile Organic Compounds (BVOCs) Emissions

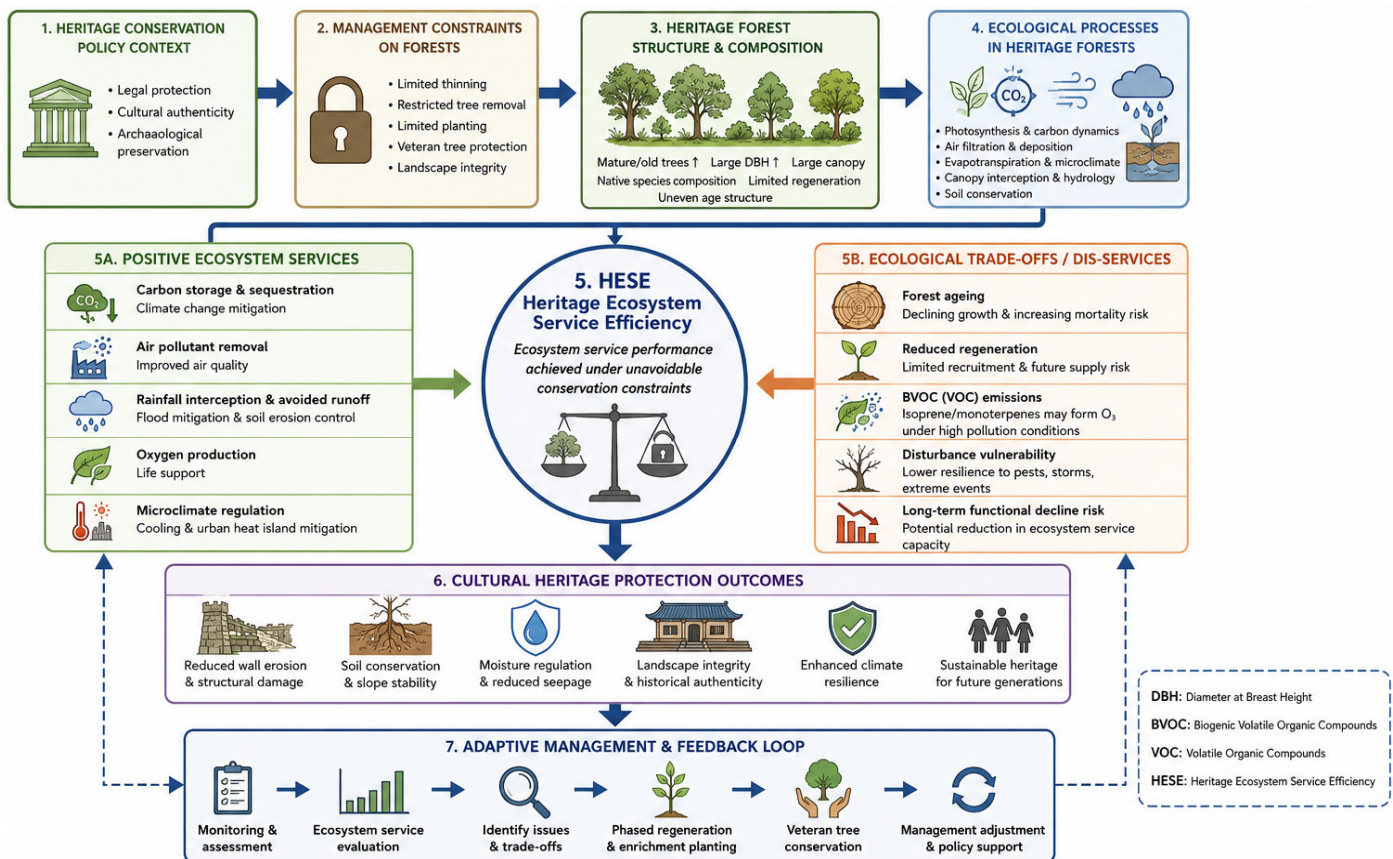
Annual emissions of BVOCs, a secondary output of the i-Tree Eco model that may represent a potential air-quality disservice under certain atmospheric conditions, were estimated at 98.16 kg/year. These emissions were driven primarily by isoprene and monoterpene production from *Quercus* species within the fortress canopy, which are widely recognized as among the highest biogenic VOC emitters in urban forest inventories [26]. Despite their relatively lower abundance compared with *Z. serrata*, *Q. glauca* and *Q. myrsinifolia* contributed disproportionately to total BVOC emissions because of their species-specific emission characteristics incorporated in the Korean i-Tree Eco parameterization. In contrast, *Z. serrata*, although the dominant contributor to carbon storage, carbon sequestration, air pollutant removal, and runoff mitigation, exhibited comparatively lower BVOC emissions relative to its overall ecosystem service contribution. This contrast highlights substantial interspecific variation in atmospheric emissions among the dominant tree species. Generally, the estimated BVOC emissions remained considerably lower than the quantified ecological benefits of the forest, including 123.1 kg yr<sup>-1</sup> of air pollutant removal, 200.7 t of carbon storage, and 8.834 t yr<sup>-1</sup> of annual carbon sequestration, indicating that the net ecosystem service balance of the heritage forest remained strongly positive.

## 4. Discussion

This study quantified the full range of i-Tree Eco-derived ecosystem services provided by the historic landscape forest of Jinju Fortress, establishing a comprehensive, species-level baseline for ecosystem service management in a nationally designated cultural heritage site. The results demonstrate that a structurally mature, spatially constrained, deciduous-dominated forest can simultaneously provide substantial and economically valuable ecosystem services across all evaluated categories. Notably, the per-tree efficiency of ecosystem service delivery at Jinju Fortress, particularly for carbon sequestration and oxygen production, exceeded values reported in all comparable Korean studies employing the i-Tree Eco framework.

Beyond the site-specific findings, the results suggest a broader conceptual implication for the evaluation of heritage landscape forests. Unlike conventional urban forests, heritage forests operate under unique conservation constraints that limit management interventions such as species replacement, large-scale planting, canopy restructuring, or stand-density optimization. Consequently, their ecological performance should not be assessed solely on the basis of total ecosystem service outputs. We propose the concept of Heritage Ecosystem Service Efficiency (HESE), defined as the capacity of protected heritage forests to maximize ecosystem service delivery while maintaining cultural authenticity, historical integrity, and conservation requirements. Under this framework, the ecological value of a heritage forest is evaluated in relation to the management constraints under which ecosystem services are produced. The relatively high per-tree carbon sequestration and oxygen production observed at Jinju Fortress illustrate how mature heritage trees can achieve high ecosystem service efficiency despite spatial limitations and restricted management

options. The HESE concept provides a transferable framework for evaluating ecosystem service performance across culturally protected landscapes, including fortress forests, royal gardens, temple forests, archaeological parks and other heritage sites worldwide. The conceptual relationships among conservation constraints, forest structure, ecosystem processes, ecosystem service trade-offs, and adaptive management embodied in the HESE framework are illustrated in (Figure 4).



**Figure 4.** Heritage Ecosystem Service framework illustrating how heritage conservation policies and management constraints shape forest structure, ecological processes, ecosystem service delivery, ecological trade-offs, and adaptive management to achieve long-term cultural heritage protection. The framework conceptualizes ecosystem service performance as a function of conservation constraints performance rather than absolute ecosystem service production alone.

#### 4.1. Heritage Ecosystem Service Efficiency as a Framework for Heritage Forest Assessment

As illustrated in Figure 4, the HESE framework extends existing ecosystem service theory by recognizing that ecosystem service performance should be evaluated relative to management constraints rather than absolute service outputs alone. In conventional urban forests, management interventions are often designed to maximize canopy cover, biomass accumulation, or ecosystem service production [37,38]. In contrast, heritage forests must simultaneously satisfy ecological, cultural, historical and aesthetic objectives. Consequently, ecosystem service efficiency rather than ecosystem service quantity may represent a more appropriate indicator of ecological performance. Under the HESE framework, mature trees become particularly important because they generate disproportionately high ecosystem service outputs while requiring a minimal disturbance to protected cultural landscapes. This perspective may be applicable across a wide range of heritage forest systems, including royal gardens, fortress forests, temple landscapes, archaeological parks, and UNESCO cultural heritage sites.

In this study, pronounced concentration of ecosystem service provision in *Z. serrata* for 40.7%–61.3% of total provision across all categories, reinforces the well-established principle that species composition is a primary determinant of urban forest ecosystem performance [32,39]. Consistent with previous research, a small number of dominant species contributed disproportionately to aggregate ecosystem service outputs regardless of site type. From a management perspective, these findings underscore the critical importance of maintaining the health, structural integrity, and long-term survival of existing large-stature *Z. serrata* at Jinju Fortress. Given its dominant contribution to ecosystem functioning, any management intervention that could result in the removal, decline or degradation of these trees should be carefully evaluated against the quantified ecosystem service losses identified in this study. Such evidence-based assessments are particularly important in heritage landscapes, where conservation objectives must be balanced with the preservation of ecosystem functions and associated societal benefits.

The mean annual carbon sequestration rate of 10.75 kg/tree/yr recorded at Jinju Fortress represents the highest per-tree value among the Korean i-Tree Eco studies reviewed in this work. This finding is consistent with the well-established relationship between tree size and carbon dynamics. Sensitivity analysis by [26] identified DBH as the most influential input variable affecting carbon storage and sequestration estimates in i-Tree Eco, with crown light exposure and tree condition as secondary factors. Consequently, the large mean DBH of *Z. serrata* individuals at Jinju Fortress, reflecting the site's long-term protection and relatively undisturbed management history as a cultural heritage landscape, provides the primary mechanistic explanation for the observed superior per-tree carbon performance.

Evidence from international studies further supports this interpretation. In Ho Chi Minh City, the mature-tree dominated Tao Dan Park exhibited nearly fivefold greater annual carbon storage value than the younger-tree dominated 23/9 [34]. Similarly, in Kyoto, the highest per-tree economic benefits were associated with the largest specimens of *Z. serrata* and *Platanus × acerifolia* [40]. The consistency of these findings across diverse geographic, climatic, and cultural contexts highlights a broadly applicable principle of urban and heritage forest management: large, mature trees contribute disproportionately to ecosystem service provision and therefore represent irreplaceable ecological assets. Accordingly, the conservation of veteran trees should be regarded not only as a cultural and historic responsibility but also as a sound ecological and economic investment. Where structural safety and site conditions permit, management strategies should prioritize the preservation and maintenance of mature trees over their replacement, over replacement wherever structurally feasible.

A broader implication emerging from this study is that ecosystem service provision in heritage forests appears to be governed more strongly by the retention of mature, large-diameter trees than by stand density. This pattern contrasts with many urban greening strategies that emphasize large-scale tree planting as the primary pathway to ecosystem service enhancement. In conservation-constrained heritage landscapes, mature-tree retention may provide greater ecological returns than increasing tree numbers alone. This principle may be transferable to protected cultural landscapes worldwide where opportunities for intensive forest restructuring are limited.

At the same time, the relatively low representation of trees in the smallest DBH class ( $\leq 15.2$  cm), comprising only 13.1% of the total population, highlights a potential structural vulnerability within the Jinju Fortress forest. This demographic pattern is characteristic of many intensively managed heritage landscapes, where the preservation of mature trees often occurs in the absence of sufficient recruitment. Without proactive supplementary planting, and regeneration efforts, the current mature-dominant stand structure is likely to

transition progressively toward senescence as veteran trees reach the end of their lifespans. Such a shift would be expected to reduce the forest's capacity to deliver key ecosystem services, including carbon sequestration, air pollutant removal, and oxygen production. These interactions between mature-tree conservation, limited regeneration, and the long-term sustainability of ecosystem service provision correspond to the adaptive pathway proposed in the HESE framework (Figure 4). Specifically, the framework highlights the need for continuous monitoring, phased regeneration, veteran tree conservation and adaptive management to sustain ecosystem services while preserving the cultural authenticity of heritage landscapes.

Outside ecosystem service efficiency, the results highlight the importance of Heritage Forest Functional Resilience, defined as the capacity of heritage forests to maintain ecosystem service provision through successive generations of trees while preserving cultural integrity. Although mature trees currently dominate ecosystem service delivery at Jinju Fortress, the limited representation of younger age classes suggests potential long-term vulnerability. Consequently, resilience in heritage forests depends not only on conserving veteran trees but also on maintaining continuous recruitment capable of sustaining ecosystem functions across future generations.

Evidence from other urban forest systems underscores the importance of maintaining continuous age-class representation. For instance, a study by [41] reported that inadequate recruitment of native species in Jakarta's urban forests contributed to increasing dominance by exotic taxa and decline in functional diversity, leading the authors to identify native species enrichment as a priority management strategy. This recommendation is directly relevant to the Jinju Fortress landscape. The phased establishment of *Z. serrata* and other culturally and ecologically appropriate native species would promote a more balanced age-class structure, enhance long-term stand resilience, and ensure continuity of ecosystem service provision. Such an approach would simultaneously support heritage conservation objectives and safeguard the ecological functions upon which the site's environmental and socioeconomic benefits depend.

The per-hectare ecosystem service performance of Jinju Fortress, particularly for air pollutant removal (96.8 kg/ha/yr), was substantially below the highest-performing Korean sites [14] and international benchmarks, reflecting the inherent structural constraints of a heritage landscape with low tree density and a high proportion of deciduous species. A study by [32] demonstrated in California that species selection is a critical lever for air quality improvement, with Turkey oak outperforming other modeled species for O<sub>3</sub> removal efficiency. In the Korean context, this suggests that selectively increasing the proportion of native evergreen broad-leaved species in areas compatible with heritage conservation standards could materially improve year-round pollutant deposition and rainfall interception without substantially altering the cultural landscape character of the site. Such species selection decisions would benefit from scenario modeling using i-Tree Eco's planting simulation capabilities, as demonstrated by [39], who showed that adjusting the tree proportion to an optimal ratio could increase annual ecological benefit by RMB 61 million in Changchun. The development of planting recommendations grounded in quantified ecosystem service projections represents an important direction for future research at heritage landscape sites.

The economic valuations presented in this study, KRW 8.31 million/yr for pollutant removal, KRW 6.09 million/yr for carbon sequestration, KRW 29,300/yr for avoided runoff, and KRW 1.63 billion in structural replacement value, provide a policy-legible, quantified basis for communicating the ecological value of the Jinju Fortress forest to heritage managers, municipal administrators, and the general public. The structural replacement value of KRW 1.63 billion, estimated using the CTLA trunk formula method, represents the

economic cost of reconstituting the current tree population through commercial nursery purchase and professional installation, a figure that quantifies the irreversibility of mature tree loss and reinforces the economic case for preventive maintenance programs over reactive replacement. Within the broader framework of nature-based solutions for carbon-neutral cities [42], the ecosystem services quantified here can be integrated into municipal carbon accounting and green infrastructure investment planning, contributing to Korea's national commitments under the Paris Agreement and aligned with the sustainability goals of SDG 11 [43].

Future research should extend beyond regulating ecosystem services to incorporate cultural ecosystem services, biodiversity conservation value, visitor perceptions, and climate adaptation functions. Integrating i-Tree Eco outputs with social surveys, biodiversity monitoring, and microclimate modeling would enable development of comprehensive ecosystem service assessments tailored specifically to heritage landscapes. In addition, scenario-based simulations evaluating species replacement, age-class restructuring, and climate change impacts could support evidence-based planning for long-term heritage forest resilience.

Several methodological limitations should be acknowledged. i-Tree Eco assumes spatially uniform ambient pollutant concentrations across the study area, whereas actual concentrations at Jinju Fortress may vary locally due to proximity to riverside traffic corridors or the topographic enclosure effect of the stone wall. The uniform leaf storage capacity coefficient ( $SL = 0.2 \text{ mm}$ ) may not fully capture interspecific variation in canopy roughness and leaf surface characteristics that influence actual interception per event. The CTLA replacement value is based on standardized domestic unit prices and does not reflect any premium associated with the cultural heritage status of individual trees. The model's carbon calculations rely on allometric biomass equations that, while validated for comparability with locally derived methods in international contexts [44,45], may not fully capture the growth structure of *Z. serrata* under the specific site conditions of Jinju Fortress. Future studies incorporating dendrometric measurements, field-validated deposition monitoring, and locally calibrated economic coefficients would improve the precision and contextual relevance of the ecosystem service estimates. Additionally, ecosystem service dimensions not captured by i-Tree Eco, including biodiversity support, cultural and aesthetic value, microclimate regulation, noise attenuation, and pollinator habitat provision, were beyond the scope of this assessment. A comprehensive multi-method evaluation integrating these dimensions with the i-Tree Eco outputs presented here would provide a more complete accounting of the total ecological value embedded in the Jinju Fortress heritage landscape.

#### 4.2. Ecological Significance of the Species Ecosystem Service Dominance Index (SESDI) and Heritage Ecosystem Service Efficiency (HESE)

The SESDI and HESE provided complementary perspectives on species performance beyond conventional structural metrics. While the IV describes species dominance based on stand composition, SESDI integrates multiple ecosystem service categories to identify species that make the greatest overall contribution to ecosystem functioning. In the present study, *Z. serrata* exhibited the highest SESDI, confirming its dominance role in supporting carbon storage, carbon sequestration, air pollutant removal, oxygen production and runoff mitigation within the Jinju Fortress heritage forest. This finding reinforces previous studies demonstrating that large, mature broad-leaved trees contribute disproportionately to urban ecosystem services because of their greater canopy area, biomass and physiological activity [46–48].

The HESE index further distinguished ecosystem service efficiency relative to structural importance, revealing that some species provided ecosystem services disproportionately greater than expected from their abundance within the forest. This distinction

is particularly relevant in heritage forests, where conservation priorities often limited opportunities for species replacement or structural modification. Consequently, management decisions should consider not only species abundance but also ecosystem service efficiency when prioritizing conservation, restoration and supplementary planting. Similar recommendations have been proposed for urban forests emphasizing functional trait-based management and ecosystem service optimization under changing climatic conditions [49–51].

Unlike conventional forests, heritage forests are managed under strict culturally and legal conservation constraints that require maintaining historical authenticity while sustaining ecological functions. Under these conditions, the combined application of SESDI and HESE provides a practical decision-support framework by simultaneously identifying dominant ecosystem service providers and highly efficient species for long-term conservation planning. Although these indices were developed using Jinju Fortress as a case study, the methodological framework is transferable to other protected cultural landscapes where species-level ecosystem service assessments are required. Future studies should validate these indices across different climatic regions and heritage forest types and evaluate alternative weighting schemes incorporating biodiversity conservation, resilience and cultural values. The present findings demonstrate that regulating ecosystem services and ecosystem disservices should not be interpreted independently when evaluating heritage forests. Although Jinju Fortress exhibits substantial carbon storage, air pollutant removal, and rainfall interception, species specific BVOC emissions and the ecological consequences of stand ageing highlight important trade-offs that influence overall ecosystem performance. These results suggest that ecosystem service assessment in heritage forests should evolve from single-service evaluation toward an integrated framework that simultaneously considers ecological benefits and disservices, thereby providing a more balanced measure of ecosystem performance under conservation constraints.

#### *4.3. Adaptive Management Implications for Heritage Forests*

The findings suggest that management strategies should be differentiated according to the ecological and cultural functions of individual heritage forest zones. Veteran trees adjacent to fortress walls should be prioritized for long-term conservation because of their critical roles in slope stabilization, rainfall interception, carbon storage, and preservation of historical landscape integrity. In contrast, riparian zones should emphasize species that strengthen bank stability and enhance hydrological regulation, while interior recreational areas provide suitable locations for phased regeneration and enrichment planting to improve age-class diversity without compromising cultural authenticity or visitor experience. Such zone-specific adaptive management aligns with the proposed HESE framework by balancing ecosystem service optimization with heritage conservation objectives, thereby enhancing the long-term resilience and sustainability of protected heritage forests.

## **5. Conclusions**

This study provides one of the first comprehensive ecosystem service assessments of a nationally protected historic landscape forest using i-Tree Eco and demonstrates that heritage forests can deliver substantial ecological benefits despite strict conservation constraints. Although Jinju Fortress occupies a relatively small and management-restricted area, its mature tree population provides high ecosystem service efficiency, highlighting the ecological significance of conserving veteran trees within culturally protected landscapes.

Beyond the empirical findings, this study advances heritage forest ecology through the development of two complementary conceptual tools. The Species Ecosystem Service Dominance Index (SESDI) extends conventional structural dominance metrics by identify-

ing species according to their integrated contribution across multiple ecosystem service categories, while the Heritage Ecosystem Service Efficiency (HESE) framework introduces a new evaluation paradigm in which ecosystem service performance is interpreted relative to the conservation constraints under which services are generated. Unlike conventional urban forest assessments that primarily emphasize maximizing ecosystem service quantity, the HESE framework recognizes that heritage forests must simultaneously maintain ecological functions, cultural authenticity, historical integrity, and legal protection. This perspective represents a theoretical extension of urban forest ecosystem service assessment for conservation-constrained landscapes.

The findings further suggest a general management principle applicable beyond Jinju Fortress: in protected heritage forests, retaining large, mature trees often provides greater long-term ecosystem service benefits than increasing tree numbers alone, while maintaining continuous regeneration is essential for sustaining ecosystem functions across future generations. Accordingly, effective heritage forest management should balance veteran tree conservation with phased recruitment and adaptive management to preserve both ecological performance and cultural values.

Although developed using Jinju Fortress as a case study, the combined SESDI-HESE framework provides a transferable analytical approach for evaluating ecosystem service performance in other culturally protected forests, including fortress forests, royal gardens, temple forests, archaeological parks, and UNESCO cultural heritage landscapes worldwide. By integrating ecosystem service efficiency with conservation constraints, the framework establishes a foundation for future comparative studies and supports the incorporation of ecosystem service valuation into evidence-based cultural heritage conservation and management. This broader conceptual contribution extends the application of ecosystem service theory from conventional urban forests to heritage landscapes, where ecological sustainability and cultural preservation must be achieved simultaneously.

## 6. Limitations and Future Research

Although i-Tree Eco v6 provides a robust framework for quantifying regulating ecosystem services, the estimates are subject to uncertainties arising from generalized model assumptions, including standardized pollutant concentrations, species-specific physiological parameters, canopy interception coefficients, and allometric relationships. These assumptions may influence the absolute magnitude of estimated ecosystem services, although they are unlikely to alter the relative ecological importance of dominant species identified in this study. In addition, the present assessment focuses primarily on regulating ecosystem services and does not quantify cultural ecosystem services, biodiversity conservation, recreational benefits, or historical landscape values, which constitute important components of ecosystem service delivery in heritage forests. Another limitation of this study is that ecosystem services were assessed using measurements from a single assessment period. Consequently, seasonal and interannual variations associated with changes in phenology, rainfall, atmospheric pollution and climatic conditions were not captured. Long-term monitoring across dynamics and improve the robustness of ecosystem service estimates.

Future research should prioritize the development of locally calibrated i-Tree Eco parameters for Korean heritage forests to reduce model uncertainty and improve estimate accuracy. The proposed HESE framework should also be extended through scenario-based analyses evaluating alternative species compositions, phased regeneration strategies, forest ageing and climate change impacts. Integrating biodiversity indicators, cultural ecosystem services and stakeholder perception survey into the HESE framework would enable a more comprehensive evaluation of heritage forests as coupled socio-ecological systems. Finally, long-term ecological monitoring across multiple heritage sites would facilitate validation

of the SESDI-HESE framework, improve its transferability across different cultural landscapes, and strengthen its application as a decision-support tool for sustainable heritage forest conservation.

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