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# Assessment of Temperate Deciduous Forest Communities and Structures after Restoration through the Multi-Reference Ecosystems Framework

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**Abstract:** The reference forest serves as a model for forest ecosystem restoration and can be employed to assess the vegetation of the Restored Forest, thereby confirming the success of restoration. When evaluating restoration, employing multireference forests is advantageous for discerning gradual changes in Restored Forests. However, in previous studies, their utilization has been limited to comparisons with individual ecosystems. Therefore, this study investigates the status of Restored Forests in previously damaged areas and their resemblance to reference forests across four forest types, namely Climax Forest (CF), Secondary Forest (SF), Restored Forest (RF), and Planted Forest (PF). Reference forests, serving as model targets for restoration, include CF and SF, while RF and PF represent the restoration forests. Six target sites within two temperate deciduous forests (*Quercus acutissima* and *Quercus variabilis*) were selected, and a comparative analysis of species diversity, dominance, and evenness was conducted. This study revealed that the dominant species in the top canopy of restoration forests mirrored those in reference forests, with *Q. variabilis* and *Q. acutissima* being prevalent. A similarity index of over 60% and a high correlation of 0.987 were observed in the top canopy layer between the reference and restored ecosystems (CF-RF/SF-PF). These findings enhance our understanding of the current status of Restored Forests and advocate for the utilization of multiple reference forests for successful restoration efforts.

**Keywords:** canopy layers; ecological similarity; urban forest; restoration successions; reference sites

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## 1. Introduction

Forest ecosystems are currently deteriorating due to urbanization-induced damages resulting in the loss of biodiversity, decline in species populations, and habitat degradation [1]. Consequently, efforts are currently being made to restore these ecosystems [2]. The aim of restoring is to reinstate the ecosystem's original structure and function, thereby reestablishing its predamage state as much as possible [3,4]. However, restoring a forest ecosystem to its original state is challenging due to difficulties in fully addressing the issues of damaged soil and variable climate conditions, which limit the complete restoration of the forest's original functions. Therefore, to facilitate ecological recovery, it becomes imperative to employ a restoration approach that is based on the ecological conditions existing prior to the onset of deterioration.

The evaluation that is carried out following forest restoration is an assessment of the effectiveness of the restoration process and plays a crucial role in determining the achievement of the set objectives [5,6]. Forest ecosystem restoration assessments are conducted by calculating species diversity, evenness, and similarity, with a primary focus on canopy structure indicators, including vegetation height and layer diversity [7,8]. These indicators have been used in previous research to evaluate the progress of restoration. For example,

quantitative criteria for their assessment have been established by utilizing vegetation structure indicators within naturally regenerated Secondary Forests [9,10]. Furthermore, to assess the environmental degradation and the degree of restoration in mining areas, the damage derived from reduced vegetation coverage has been quantitatively evaluated through the analysis of vegetation height and coverage values [11]. However, forest ecosystem restoration assessments using the vegetation index have limitations in determining the success of restoration because a long time is required to achieve the ideal target ecosystem. Therefore, to comprehensively evaluate the progress and efficiency of restoration, it is important to use a reference forest ecosystem that serves as a standard [12,13].

Reference forests are a standardized ecological system that represents the ultimate objective of efforts aimed at restoring compromised forest ecosystems [14]. They serve as an initial diagnostic tool for gauging progress toward the ultimate restoration objective [15]. Presently, reference forests are predominantly used as a tool for the restoration of degraded forest areas and assessment of restoration efficacy. For example, restoration assessments employing reference forests involve the comparison of vegetation indicators (canopy structure and species diversity) between restoration and reference forests [16]. Oyake et al. (2019) employed a comparative analysis of the dominant species composition between the initially degraded area and the near-reference forest [17], carried out 33 years post-restoration, to assess the success of the restoration process. Furthermore, O'Connell et al. (2022) verified successful restoration by comparing and evaluating the vegetation networks of one restored mangrove forest and reference forest [18]. However, previous research has generally been centered on unidimensional restoration assessments constrained within a single reference forest ecosystem. This approach has limitations in the long-term evaluation of restoration outcomes within forest ecosystems characterized by gradual changes in the canopy structure. Consequently, it is imperative to determine the success of restoration by referring to a range of forest ecosystems, considering the continual processes inherent in them [19].

Therefore, this study determines the current status of Restored Forest ecosystems by comparing the vegetation status of Restored Forest ecosystems with two reference forest types in different regions. Specifically, we utilize the vegetation structure index to (1) compare the layer-by-layer community structure of the reference forest and the Restored Forest, and (2) employ the similarity index and cluster analysis to evaluate whether the Restored Forest exhibits similar attributes to the reference forest.

## 2. Materials and Methods

### *2.1. Selection of Four Forests*

In this study, the investigated forests were classified into two groups: restoration forests and reference forests (Figure 1). Reference forests serve as a model for the restoration of damaged forest ecosystems, offering essential guidance for the restoration process. Restoration forests, conversely, are areas where damaged ecosystems undergo reforestation based on reference forest models (Figure 1). These two groups comprise two restoration forests and two reference forests that serve as templates during the creation of the restoration forests, totaling four forests in the study.

The selection of reference forests and restoration forests took into account locational characteristics, forest types, and reference ranges. Reference forest areas were designated following a comprehensive assessment of locational attributes, which included considerations of geographical features such as mountains and ridges, as well as adherence to the climatic zone typical of the Korean Peninsula. Simultaneously, the survey areas were characterized by a vegetation composition resembling that of the natural forest ecosystem. In instances where a similar area could not be identified, a local ecosystem within a 3 km radius, possessing comparable locational attributes to the restoration forest, was chosen. The selected forest types were *Q. variabilis* and *Q. acutissima* communities, representing dominant species within the study area and characteristic of natural temperate deciduous forests.

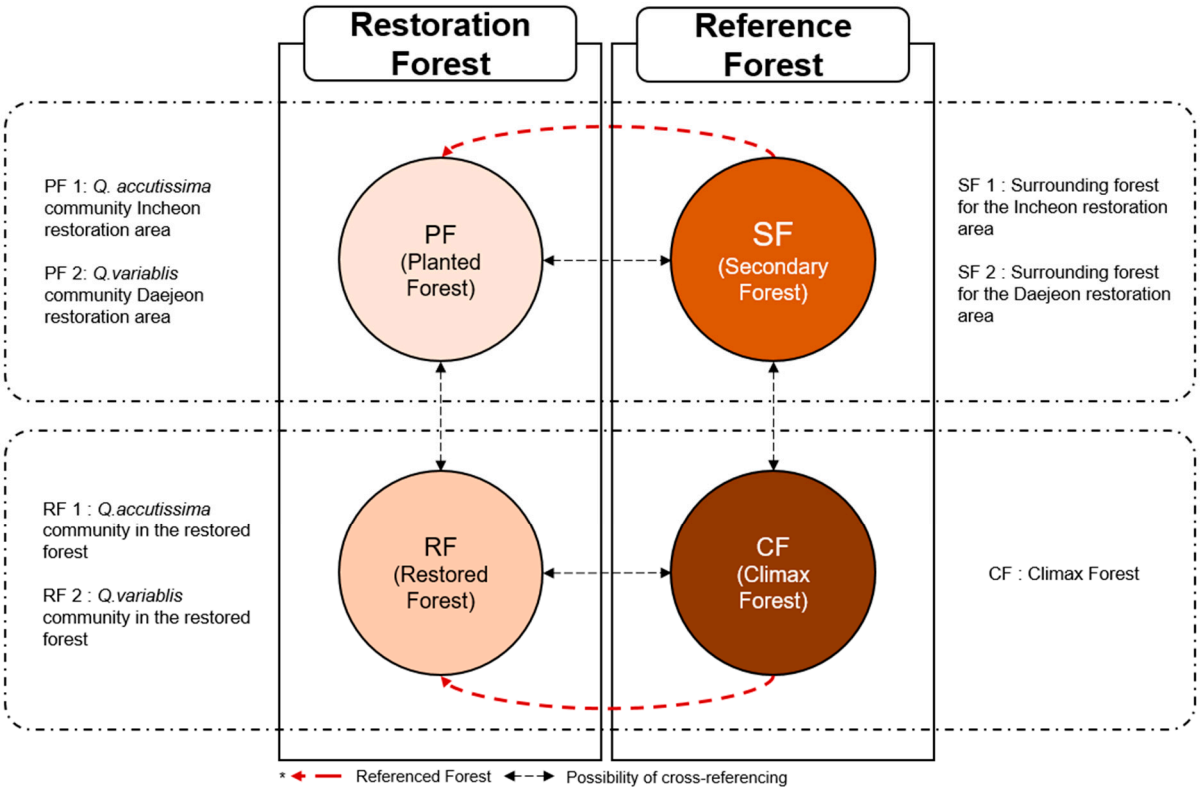


**Figure 1.** Diagram of the study sites classified based on reference criteria. PF, Planted Forest in the restoration park; RF, Restored Forest in NIE, which was restored using the CF as a reference; SF, Secondary Forest located around the RF; CF, Climax Forest (ideal forest).

The restoration forests category includes Planted Forest (PF), representing a forest rehabilitated after damage, and Restored Forest (RF), restored within an ecological conservation and education area to enhance species diversity. The reference forests category comprises Climax Forest (CF), symbolizing the optimal ecosystem in the succession process, and Secondary Forest (SF), indicative of the forest surrounding the restored area. The targeted site within the four forests was an area where both vegetation communities existed. Therefore, eight survey areas were selected, each characterized by the presence of two vegetation communities within the four forest regions.

Planted Forest (PF) designates an urban area forest that experienced damage and underwent restoration to transform into an ecological park. The restoration process for PF involved referencing nearby forests to introduce a stable forest composition. In this study, neighboring forests were designated as Secondary Forests (SFs), serving as reference forests for the restoration of Planted Forest (PF). Restored Forest (RF) was planted within the National Institute of Ecology's (NIE) premises in Korea to reinstate and enhance biodiversity. RF drew references from Climax Forests, serving as the ideal objective forest for the restoration of vegetation communities across all climate zones on the Korean Peninsula within the NIE. The Climax Forest (CF) denotes a forest ecosystem characterized by the coexistence of vegetation types representative of climatic zones, including evergreen broad-leaved forests in warm temperate regions, deciduous forests in warm temperate zones, temperate deciduous forests, and boreal forests. CF was utilized to replicate and restore RF.

### *2.2. Study Sites and Vegetation Survey*

The field survey covered four out of the eight designated survey areas, namely PF, SF, and PF, which were accessible for direct investigation and data collection. Due to constraints in conducting on-site surveys, data for the remaining four survey areas, including CF along with selected SF and RF sites, were derived from existing field survey monitoring data.

Monitoring data from 2011 and 2016 were utilized for CF and RF, while data for SF and PF were obtained from a combination of on-site vegetation surveys conducted between May and August 2019 and existing monitoring data.

Sampling within the survey area was carried out at a scale of 100 $m^2$, using the Braun-Blanquet survey method (1932). Vegetation survey data were collected for height, coverage, and density across three layers of trees within the four samples. The classification of layer height followed the Raunkiaer system, with adjustments made to accommodate the vegetation specific to the climatic zones of the Korean Peninsula. Accordingly, the top canopy was defined as 8 m or greater, the sub-canopy ranged from 2 to 8 m, and the shrub layer was delineated as 2 m or less. The species coverage index was calculated as the proportion of the total area occupied by a particular species, while species density was determined by number of trees within the entirety of the surveyed area.

#### 2.2.1. PFs in the Restoration Park

The PF site, situated in an urban environment, represents an area that underwent degradation but was subsequently rehabilitated to form an ecological park. This PF is found within the ecological parks of Incheon and Daejeon, characterized by temperate deciduous trees, particularly *Q. acutissima* and *Q. variabilis*, which are emblematic of broad-leaved species aligning with the climate zone of the Korean Peninsula. The dataset for the two PF sites was generated through the measurement of tree height and quantity across various layers within a 100 $m^2$ survey area. Additionally, measurements of relative coverage (%) and relative density (%) were conducted.

- PF 1: Incheon restoration area

Site PF 1 is situated in the restored park at 414-1 Yeonhui-dong, Seo-gu, Incheon, South Korea (Figure 2A-1, 37°54′65.27″ N, 126°66′23.04″ E, area: 1767 $m^2$). PF 1 was established by referencing the composition of the adjacent forest (Figure 2A-2; SF 1). The dominant species in the top canopy layer is *Quercus acutissima* (Table A1 in Appendix A). The sub-canopy layer is composed of *Sorbus alnifolia* K. Koch, *Lindera obtusiloba*, and *Acer pseudosieboldianum* Kom., while the shrub layer includes *Rhododendron mucronulatum*, *Stephanandra incisa*, *Callicarpa japonica*, and *Lespedeza maximowiczii*.

- PF 2: Daejeon restoration area

Site PF 2 is a restored *Quercus* forest situated in the restored park at 910 Dunsan-dong, Seo-gu, Daejeon, South Korea (Figure 2B-1; 36°35′90.55″ N, 127°38′50.83″ E). Established in 2015, this site involved the planting of trees sourced from Daejeon Useongsan Mountain, located 2.5 km away from the PF 2 site, serving as the reference forests (SF 2). The dominant species, *Q. variabilis*, along with *Q. aliena*, constitutes the top canopy layer (Table A2 in Appendix A). The sub-canopy layer includes *Q. variabilis* and *Q. aliena*, while the shrub layer features *S. prunifolia*, *L. obtusiloba*, and *V. erosum*.

#### 2.2.2. RF in Seocheon

The RF site is an ecological forest situated in the National Institute of Ecology at 1210 Geumgang-ro, Maseo-myeon, Seocheon-gun, Chungcheongnam-do, South Korea (Figure 2C; 36.02° N, 126.43° E, area: 33,824 $m^2$). Established to revitalize native plant habitats and preserve biodiversity, RF plantings aimed to replicate and restore the species composition, canopy structure, and population density observed in an ideal forest (CF). This strategy sought to facilitate adaptation to climate change and promote optimal succession processes. Throughout the restoration, specialists from the National Institute of Ecology (NIE) assessed the relative density, coverage, and height of *Q. acutissima*, *Q. variabilis*, *Q. mongolica*, and *Pinus densiflora* communities in the CF. These communities represent warm temperate evergreen broad-leaved forests, temperate deciduous broad-leaved forests, and cool temperate forests. The RF restoration involved approximately 310 plant species distributed across 14 ecological communities, totaling 205,900 plants. This study evaluated

the relative density, coverage, and height of *Q. acutissima* and *Q. variabilis* communities in the RF.

#### 2.2.3. SFs Near the Restoration Park

In this study, SF was selected as the forest in proximity to PF within the regions of Daejeon and Incheon. Direct monitoring of SFs in Daejeon posed challenges, leading to the utilization of data from the National Institute of Ecology (NIE) as an alternative information source [20]. The data, obtained through surveys and analyses of forest environments adjacent to degraded areas, served as a resource for guiding the restoration of damaged urban areas. Furthermore, in regions where on-site field investigations were feasible, such as Incheon, comprehensive field studies were conducted, focusing on the forest ecosystems surrounding PFs. The collected data included information on dominance, coverage, and the composition of each layer within SF.

- SF 1: reference for PF 1 (Incheon restoration area)

SF 1, located in proximity to PF 1 (37°54′72.12″ N, 126°66′18.12″ E, area: 2433 $m^2$), was selected as the reference forest for PF 1 (Figure 2A-2). The on-site vegetation survey of SF 1 involved measuring the height and quantity of trees across three layers within a 10 m × 10 m square. A field-based vegetation survey of SF 1 yielded a total of 12 species. *Q. acutissima* emerged as the dominant species in both the top canopy and sub-canopy layers, accompanied by *Magnolia kobus* in the sub-canopy layer and *P. sargentii* in the shrub layer. The average tree height measured 9.8 m, with *Q. acutissima* exhibiting the tallest trees at 17.8 m, and *Prunus sargentii* Rehder being the shortest with heights ranging from 2.0 to 2.5 m. *Q. acutissima* also achieved the highest relative coverage in the sub-canopy layer at 75%.

- SF 2: reference for PF 2 (Daejeon restoration area)

SF 2, situated at Wooseong mountain in Doryong-dong, Yuseong-gu, South Korea (36°38′50.49″ N, 127°38′50.44″ E), was designated as the reference forest for PF 2. Data for SF 2 were primarily sourced from previous monitoring surveys, given the challenges associated with direct on-site investigations [20]. A total of 46 sites were included in the analysis, with data from seven forest locations adjacent to urban areas damaged in 2016. Additional information from 39 sites surveyed in 2014 was also incorporated. The *Q. variabilis* community in SF 2, when considering all stratigraphic structures and communities targeted for restoration, exhibited dominant species in each layer as follows: *Q. variabilis* in the top canopy layer; *R. trichocarpa*, *S. japonicus*, and *P. serrulata* in the sub-canopy layer; and *R. mucronulatum* and *L. obtusiloba* in the shrub layer.

#### 2.2.4. CF (Climax Forest)

The target site selection for the Climax Forest (CF) was based on comprehensive field survey data from diverse locations across the country, encompassing forests representative of the climate zone of the Korean Peninsula, for the establishment of the Restored Forest (RF). Field surveys were conducted by a collaborative team consisting of researchers from Kongju University in Korea and the Ministry of Environment [21]. The survey was conducted at 10 standard sites per region. The climate zone of the Korean Peninsula includes temperate evergreen broad-leaved forests, temperate deciduous broad-leaved forests, and boreal forests. Nine forest areas, representing 13 vegetation communities, such as *Q. acutissima* and *Q. variabilis*, *Camellia japonica* L., and *Quercus acuta* Thunb communities, were selected as standard field sites within the climate zone of the Korean Peninsula. In this study, data from two regions representing the *Q. acutissima* and *Q. variabilis* communities among the 13 communities were utilized.

The region representing the *Q. acutissima* community is a forest situated in Yesan, Chungcheongnam-do, South Korea (36°33′00.4″ N, 126°20′51.8″ E, area: 100 $m^2$). In the *Q. acutissima* community, *Q. acutissima* was verified as the dominant species in the top canopy

layer. The dominant species in the sub-canopy layer was *Q. serrata*, while in the shrub layer, it was *Indigofera kirilowii*.

The region representing the *Q. variabilis* community is a forest situated in Woraksan National Park, positioned on the border between Chungju-si, Chuncheongbuk-do, and Mungyeong-si, Gyeongsangbuk-do (36°53′31.4″ N, 128°08′44.9″ E, area: 400 $m^2$). In the *Q. variabilis* community, *Q. variabilis* was confirmed as the dominant species in the top canopy layer. In the sub-canopy layer and shrub layer, the dominant species were identified as *Q. serrata* and *Carex humils* var. *nana* Owi.

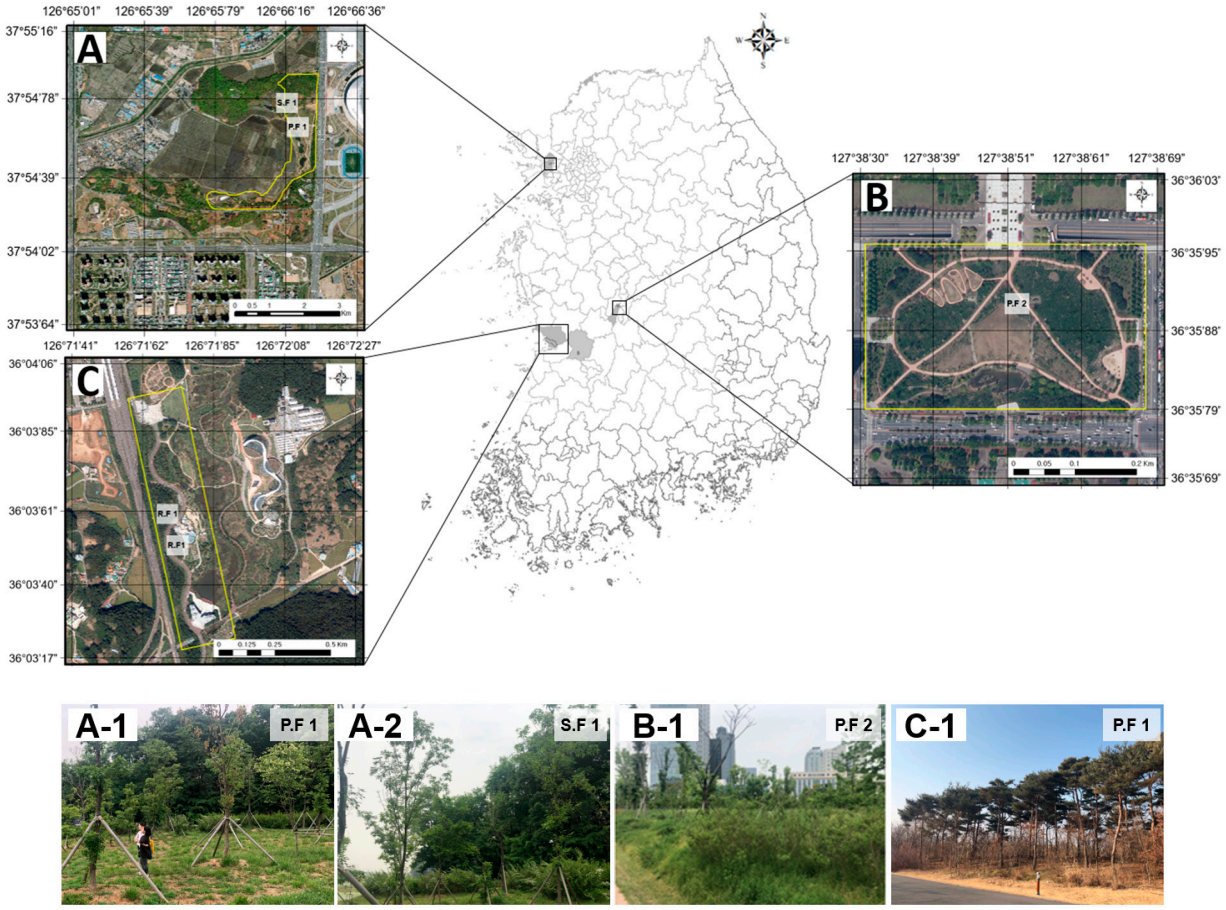


**Figure 2.** Locations of the study sites: (**A**) Incheon Restored Park, PF1 (**A-1**), SF1 (**A-2**); (**B**) Daejeon Restored Park, (**B-1**) PF2; (**C**) Restored Forest in Seocheon, (**C-1**) RF (PF, Planted Forest; RF, Restored Forest; SF, Secondary Forest).

### *2.3. Canopy Structure Analysis Using Previously Collected Monitoring Data and Field Survey Data*

Canopy structure assessment involved quantifying the height, density, coverage, and number of trees within each vegetation layer of both the reference forests (CF, SF) and restoration forests (RF, PF). Evaluation of canopy structure in reference and restoration forests utilized Shannon's species diversity, abundance, and dominance indices. This assessment encompassed parameters such as height, relative density, and relative coverage of the tree layers. Species diversity, indicating the extent of diversity in species composition, was quantified. Also, evenness, assessing the uniform distribution of species within a community, was evaluated using species diversity and maximum species diversity. Dominance is a measure that signifies the level of predominance exhibited by a species within a specific area, and its quantification was derived through the evenness. In this study, when both evenness and dominance values exceed 0.9, they suggest a uniform representation of species and dominance by a specific species, respectively. Relative coverage refers to the proportion of coverage contributed by a particular species relative to the aggregate

coverage of all species examined. Similarly, relative density denotes the density of a particular species relative to the cumulative densities of all species surveyed, expressed as a percentage.

### *2.4. Comparative Evaluation of Similarity between the Restoration Forests and Reference Forests*

Similarity index and cluster analyses were conducted to assess the similarity across three layers between the reference forests (CF, SF) and the restoration forests (RF, PF). Similarity indices quantify the relatedness between species within vegetation communities [22]. In this study, the similarity analysis aimed to assess the resemblance of species composition across layers between restored and reference forests. The SI index was computed based on relative coverage following Whittaker's methodology (1956). In this study, similarity was considered high when the similarity index value between clusters reached 60% or higher [23]. Cluster heatmap analysis is employed to ascertain vegetation species composition and similarity between communities [24]. In this study, cluster heatmap analysis was performed to assess the correlation and similarity in species composition between restored and reference forests. The analysis utilized the relative coverage of species, and a *t*-test was conducted to verify the correlation and statistically confirm the species composition between the restoration forest and the reference forests. The cluster heatmap was created using the Heatmaply package in R (version 3.44) [25].

## 3. Results

### *3.1. Vegetation Characteristics of Restoration Forests*

As a result of identifying the number of trees, relative cover, species diversity, dominance, and evenness across different layers of the restoration forests, it was observed that both the sub-canopy and shrub layers exhibited higher relative coverage and larger populations compared to the top canopy layer of the restoration forests (Figure 3).

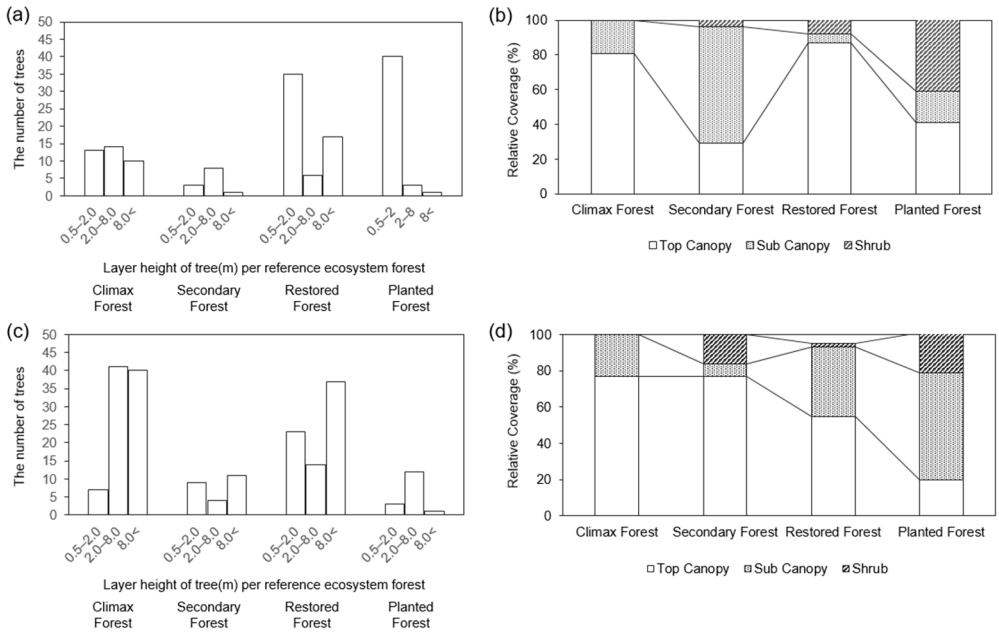


**Figure 3.** The number of trees (**a**,**c**) and relative coverage (**b**,**d**) for restoration forests and reference forests by layer. (**a**,**b**) represent the *Q. acutissima* Carruth community. (**c**,**d**) represent the *Q. variabilis* Blume community. The top canopy layer, sub-canopy layer, and shrub layer include vegetation with heights of ≥8 m, 2–8 m, and 0.5–2 m, respectively.

Within the *Q. acutissima* community, the shrub layer of the PF exhibited the highest individual count, comprising a total of 40 individuals, including *Weigela subsessilis*, *Q.acutissima*, and *Corylopsis coreana*. Moreover, this layer demonstrated a higher relative coverage of 41% compared to other layers (Figure 3). Simultaneously, it was verified that

the species diversity of the shrub layer measured 0.1408, higher than the values observed in other layers (Figure 4).

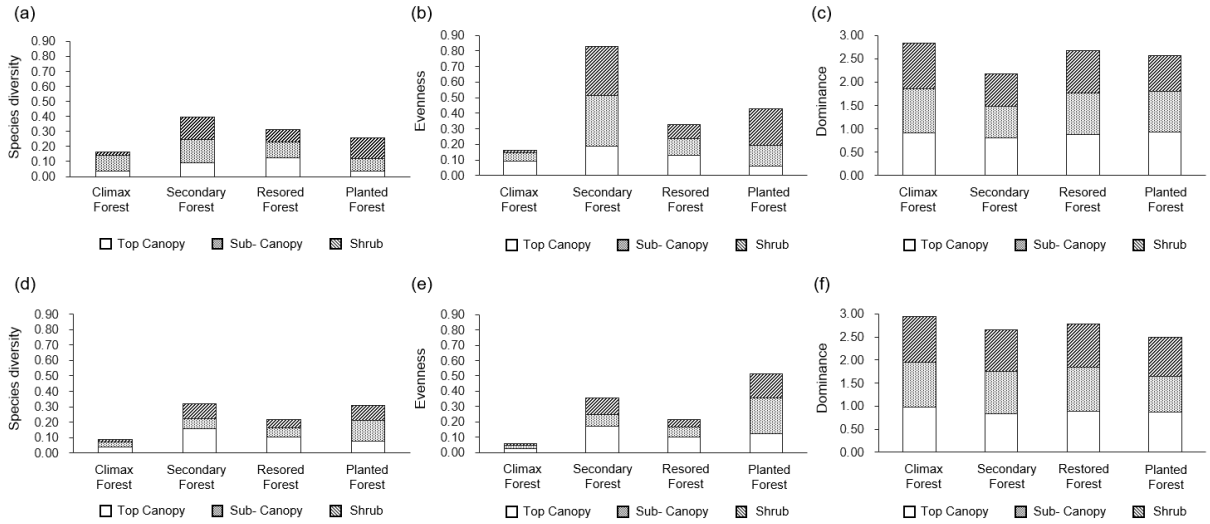


**Figure 4.** Comparison of species diversity (H′), evenness (J′), and dominance (D) between reference forests and restoration forests. (**a**–**c**) represent *Q. acutissima* Carruth community. (**d**–**f**) represent *Q. variabilis* Blume.

Upon a comprehensive examination of the community structure of the restoration forests, it was observed that in contrast to the reference forest SF, species diversity and evenness were low, while dominance exhibited a high value. The restoration forests present a range of 0.2169 (±0.0268) to 0.3108 (±0.0268) for species diversity, 0.2169 (±0.0268) to 0.5112 (±0.0539) for evenness, and 2.4888 (±0.0268) to 2.7831 (±0.0539) for dominance (Figure 4). In particular, in the *Q. acutissima* community, the species diversity value of PF was 0.2577 (±0.0520), the evenness value was 0.4279 (±0.0864), and the dominance value was 2.6743 (±0.0217). In the *Q. variabilis* community, the species diversity value of PF was 0.2169 (±0.0268), the evenness value was 0.2169 (±0.0268), and the dominance value was 2.6743 (±0.0268) (Figure 4).

### *3.2. Identification of Dominant Species by Layer Based on Restoration Forests and Reference Forests*

The dominant species in the top canopy layer of both the restoration forests and the reference forests within the two communities were identified as *Q. acutissima* and *Q. variabilis*, respectively (Figure 5). Additionally, in the *Q. variabilis* community, the species composition, excluding the dominant species in the top canopy layer, exhibited similarities between ecosystems that were mutually referenced (CF-RF; SF-PF). In particular, *Quercus aliena Blume* and *Platycarya strobilacea* were different as common species in the top canopy layers of both CF and RF.

Conversely, the dominant species and species composition in the sub-canopy layer and shrub layer differed between the restoration forests and the reference forests within each community (Figure 5). In particular, the dominant species in the sub-canopy layer and shrub layer within the *Q. acutissima* community were identified as *Prunus sargentii Rehder*, *Q. acutissima*, *Quercus serrata*, and *Acer palmatum* Thunb. Also, the dominant species in the sub-canopy layer and shrub layer within the *Q. variabilis* community were identified as *Quercus mongolica* Fish. ex Ledeb, *Quercus serrata*, *Q. varibilis*, and *Euonymus alatus (THUNB.)* SIEB.

Upon comprehensive consideration of relative coverage, it was observed that the relative fidelity of the top canopy layer of *Q. acutissima* in both CF and RF, which were cross-referenced, reached the highest values, specifically 81% and 57%, respectively (Figure 5). Furthermore, the top canopy layer of *Q. acutissima* in both SF and PF, which were referenced

during their planting, exhibited the highest relative coverage, with values of 77% and 20%, respectively (Figure 5).

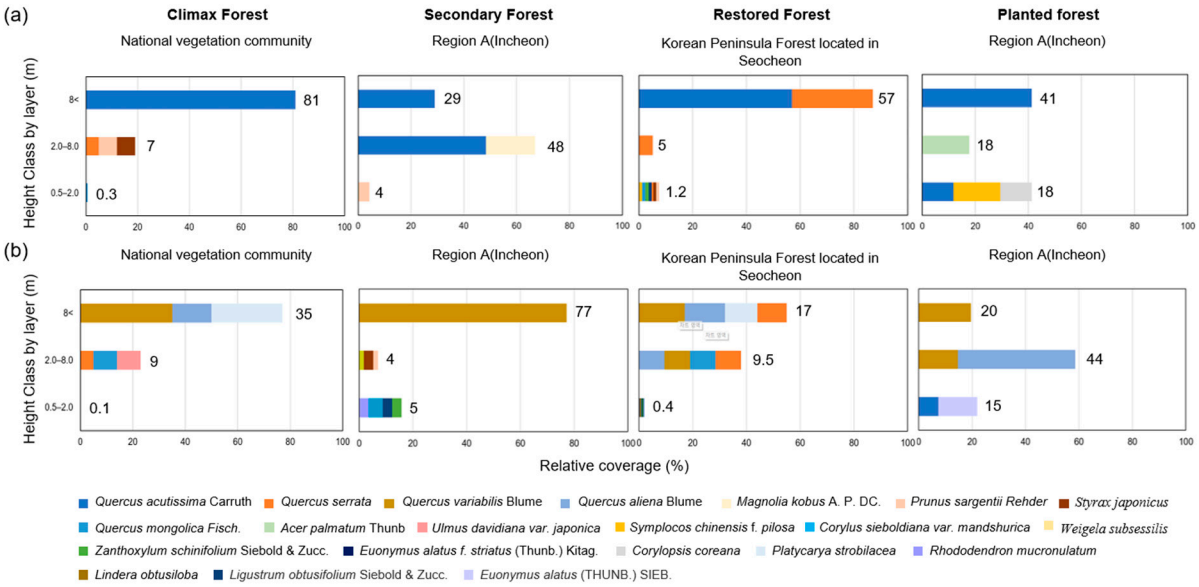


**Figure 5.** Vertical structure by restoration and reference forests. (**a**) *Q. acutissima* communities; (**b**) *Q. variabilis* communities. The numerical values in the graph indicate coverage based on the height of the dominant species.

### *3.3. Similarity between Reference and Restoration Forests*

The cluster and similarity analyses conducted between restoration forests (RF, PF) and reference forests (CF, SF) revealed that CF was similar to RF, and SF was similar to PF (Figure 6 and Table 1). In particular, the top canopy layer exhibited the highest degree of similarity, surpassing 50%, when compared to the sub-canopy and shrub layers.

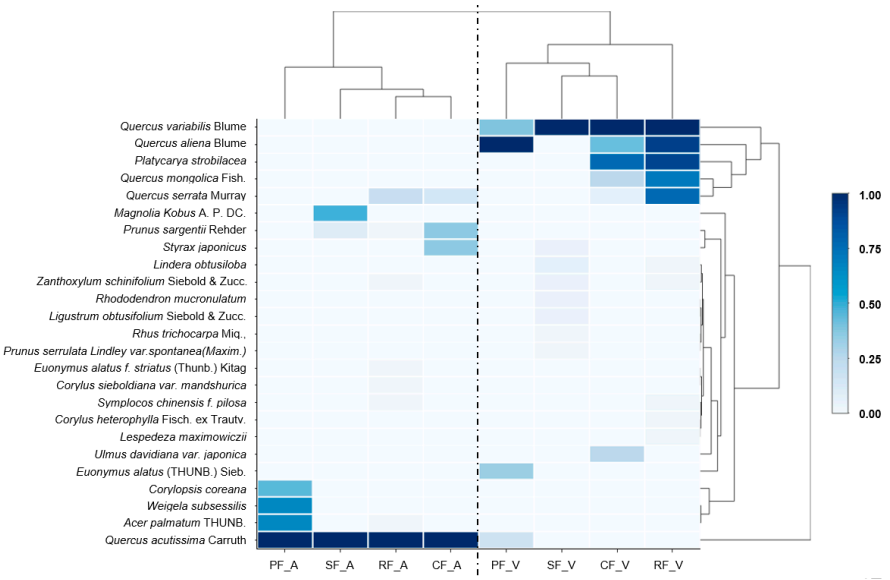


**Figure 6.** Cluster heatmap of relative species coverage of the restoration forests and reference forests. The legend on the right indicates the normalized values for the relative cover of species present in each ecosystem. The line at the top of the figure represents the clustering between reference forests, and the line on the right represents the clustering between species. The X axis indicates the forests in the study sites. Abbreviations: A, *Q. acutissima* community; V, *Q. variabilis* community; CF, Climax Forest; SF, Secondary Forest; RF, Restored Forest; and PF, Planted Forest in the restored park.

**Table 1.** Similarity index (%) between restoration forests and reference forests by vegetation community.

| | | | CF [2] | SF | RF | PF |
|---|---|---|---|---|---|---|
| *Q. acutissima* | TC [1] | CF | - | | | |
| | | SF | 53 | - | | |
| | | RF | 68 | 50 | - | |
| | | PF | 66 | 50 | 63 | - |
| | SC | CF | - | | | |
| | | SF | * | - | | |
| | | RF | 42 | * | - | |
| | | PF | 53 | * | * | - |
| | SL | CF | - | | | |
| | | SF | 0 | - | | |
| | | RF | 6 | 17 | - | |
| | | PF | 1 | * | * | - |
| *Q. variabilis* | TC | CF | - | | | |
| | | SF | 25 | - | | |
| | | RF | 67 | 33 | - | |
| | | PF | 36 | 79 | 47 | - |
| | SC | CF | - | | | |
| | | SF | * | - | | |
| | | RF | 41 | * | - | |
| | | PF | * | * | 16 | - |
| | SL | CF | - | | | |
| | | SF | * | - | | |
| | | RF | * | * | - | |
| | | PF | * | * | * | - |

[1] TC, top canopy; SC, sub-canopy; SL, shrub layer; [2] CF, Climax Forest; SF, Secondary Forest; RF, Restored Forest; PF, Planted Forest in the restored park; and *, No shared species.

Following a similarity index analysis, it was determined that the similarity value for the top canopy layer in both CF and RF within the *Q. acutissima* community was high at 68%. Additionally, the similarity value for the top canopy layers in SF and PF was high at 50% (Table 1). Within the *Q. variabilis* community, the similarity value for the top canopy layer between CF and RF reached 67%. Furthermore, the highest similarity value, reaching 79%, was observed for the top canopy layer between SF and PF. Conversely, the similarity values for the sub-canopy layer and shrub layer were comparatively lower than those observed for the top canopy layer between the restoration forests and the reference forests (Table 1). Within the communities of *Q. acutissima* and *Q. variabilis*, the similarity values for sub-canopy layers between CF and RF were 41% and 42%, respectively. However, the similarity values for the sub-canopy layers between SF and RF were not identified (Table 1). The similarity values for the shrub layer between CF and RF within the community of both *Q. acutissima* and *Q. variabilis* were either 1% or absent (Table 1).

As a result of conducting cluster and heatmap analysis for all species identified in both the restoration forests and reference forests, we classified the species into two communities: *Q. acutissima* and *Q. variablis* (Figure 6, k = 2). The correlation between the restoration forests and reference forests was found within *Q. acutissima* and *Q. variabilis*, which are the dominant species in the top canopy layer of their respective communities (Figure 6). In particular, in the *Q. acutissima* community, both CF and RF were grouped together in the same cluster. The highest correlation between CF and RF was observed within the *Q. acutissima* species, with a correlation coefficient of r = 0.987 (Figure 6). In the *Q. variabilis* community, both SF and CF were clustered together. The correlation between SF and PF reached its maximum value at r = 0.987 for *Q. variabilis*, which stands as the dominant species (Figure 6).

## 4. Discussion

This study conducted an analysis of vegetation structure and layer-wise similarity with the reference forest to evaluate the progress of restoration within the Restored Forests, guided by the reference forests. The findings indicated that the overall population and relative coverage of the Restored Forests exceeded those of the reference ecosystem. Specifically, the population and relative cover rate of the sub-canopy and shrub layers were found to be higher than those of the top canopy layer of the forest. This observation can be attributed to sub-canopy- and shrub-oriented planting practices aimed at enhancing species richness during the early stages of natural succession after restoration of the forests [6,26].

However, analysis of species diversity, evenness, and dominance in the Restored Forests revealed lower diversity and higher dominance compared to the reference forests. While forests typically exhibit diverse plant communities following disturbances such as fire or felling [27], the observed lower diversity and higher dominance in the Restored Forests are understandable given the relatively short restoration period of less than 10 years in this study. It is generally acknowledged that forest restoration in degraded areas requires more than 30 years to reach an optimal state for quantitative evaluation [28,29].

Nevertheless, a high similarity between the Restored Forest and the reference forest was observed in the top canopy layer. This similarity can be attributed to the planting of the same dominant species found in the top canopy layer of the reference forest during the restoration process. Planting the same dominant species as those in the top canopy layer of the reference forest plays a crucial role in reforestation across various biomes over an extended period [30,31]. However, the similarity of the sub-canopy and shrub layers between the Restored Forest and the reference forest was lower than that of the top canopy layer. Typically, damaged soil presents challenges in establishing species within both layers due to low pH and moisture levels, limiting the feasibility of planting the same tree species as those in the reference forest [32,33]. Therefore, the lower similarity observed in these layers in this study was attributed to the absence of commonly planted species.

This study contributed to the evaluation of restoration progress in Restored Forests by conducting a similarity analysis and comparisons with the reference forests. Restored Forests that utilize reference forests exhibit similarities to existing forests due to the successful adaptation of planted species to current environmental conditions [34]. Continuous assessment of vegetation restoration progress in the Restored Forests using reference forests is crucial as the succession process tends to accelerate after 10–20 years [35]. Furthermore, it is imperative to consider environmental variables such as soil composition, topography, and climatic conditions inherent to each ecosystem, alongside the multi-layered presence of diverse species [36]. These considerations are essential elements that, in conjunction with canopy structure, define both reference forests and Restored Forests.

## 5. Conclusions

Reference forests serve as an ideal objective for assessing the progress of restoration through post-restoration comparative evaluations. Past research predominantly limited the use of reference forests to individual comparisons. In contrast, this study introduced the use of multiple reference forests for a comprehensive evaluation of the status and restorative progress of damaged forests that have undergone rehabilitation. Eight target sites representing four forest types divided into two categories, i.e., reference forests and restoration forests, were analyzed by assessing vegetation structure indicators, including species richness, canopy coverage, and density. The results revealed a similar top canopy layer between the restoration and reference forests. However, it was observed that the restoration forests under examination would necessitate over a decade to attain full vegetation growth comparable to that observed in reference forests. Based on the results obtained in this study, it was concluded that the restoration of compromised forests should prioritize the introduction of dominant species into the top canopy layer and consider factors such as soil composition, topography, climate conditions, and species diversity by layer. Ultimately,

this study underscores the relevance of employing multiple reference forests to improve the evaluation of restoration progress in forest sites recovering from damage.

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## Appendix A

**Table A1.** Results of vegetation characteristics by reference forest in *Quercus acutissima* community.

| | | | Dominant Species | The Number of Trees | Average Height (m) | Relative Coverage (%) | Relative Density (%) | Sites |
|---|---|---|---|---|---|---|---|---|
| *Quercus acutissima* | CF [2] | TC [1] | *Quercus acutissima* | 8 | 17.0 | 81.0 | 35.0 | Yesan, Chungcheongnam-do |
| | | SC | *Quercus serrata* | 11 | 6.0 | 5.0 | 48.0 | |
| | | | *Prunus sargentii* | 1 | 6.0 | 7.0 | 4.3 | |
| | | | *Styrax japonicus* | 1 | 6.0 | 7.0 | 4.3 | |
| | | SL | *Quercus serrata* | 1 | 3.5 | 0.3 | 4.3 | |
| | | | *Quercus acutissima* | 1 | 3.5 | 0.3 | 4.3 | |
| | SF | TC | *Quercus acutissima* | - | 17.0 | 29.0 | - | Restored park at 414-1, Yeonhui-dong, Seo-gu, Icheon |
| | | SC | *Quercus acutissima* | - | 6.0 | 48.0 | - | |
| | | SL | *Prunus sargentii* Rehder | - | 2.0 | 4.0 | - | |
| | RF | TC | *Quercus acutissima* | 8 | 8.0 | 57.0 | 8.3 | Ecological forest situated in National Institute of Ecology at 1210, Guemgang-ro, Maseo-myeon, Seocheon-gun, Chungcheongnam-do |
| | | | *Quercus serrata* | 9 | 8.0 | 30.0 | 9.4 | |
| | | SC | *Quercus serrata* | 6 | 2.5 | 5.0 | 6.3 | |
| | | SL | *Indigofera kirilowii* Maxim. ex Palib | 40 | 0.5 | 1.2 | 41.7 | |
| | | | *Symplocos chinensis* f. *pilosa* | 2 | 0.5 | 1.2 | 2.1 | |
| | | | *Corylus sieboldiana var. mandshurica* | 2 | 0.5 | 1.2 | 2.1 | |
| | | | *Zanthoxylum sxhinifolium* S. et. Z. | 2 | 0.5 | 1.2 | 2.1 | |
| | | | *Euonymus alatus* f. *striatus* (Thunb.) | 3 | 0.5 | 1.2 | 3.1 | |
| | | | *Quercus serrata* | 11 | 0.5 | 0.5 | 11.5 | |
| | | | *Styrax japonicus* | 6 | 0.5 | 1.1 | 6.3 | |
| | | | *Corylus sieboldiana var. mandshurica* | 7 | 0.5 | 1.1 | 7.3 | |
| | PF | TC | *Quercus acutissima* | 1 | 8.0 | 41.2 | 2.3 | Restored park at 414-1, Yeonhui-dong, Seo-gu, Icheon |
| | | SC | *Acer palmatum* | 3 | 4.0 | 17.6 | 6.8 | |
| | | SL | *Quercus acutissima* | 5 | 2 | 11.8 | 11.4 | |
| | | | *Weigela subsessilis* | 20 | 2 | 17.6 | 45.5 | |
| | | | *Corylopsis coreana* | 15 | 2 | 11.8 | 34.1 | |

[1] TC, top canopy; SC, sub-canopy; SL, shrub layer; [2] CF, Climax Forest; SF, Secondary Forest; RF, Restored Forest; PF, Planted Forest in the restored park.

**Table A2.** Results of vegetation characteristics by reference forest in *Quercus variabilis* community.

| | | | Dominant Species | The Number of Trees | Average Height (m) | Relative Coverage (%) | Relative Density (%) | Sites |
|---|---|---|---|---|---|---|---|---|
| *Quercus variabilis* | CF [2] | TC [1] | *Quercus variabilis* | 25 | 12.0 | 35.0 | 45.0 | Woraksan National Park, Chungju-si, Chucheongbuk-do, Mungyeong-si, Gyeonsanbuk-do |
| | | | *Quercus aliena* Blume | 4 | 12.0 | 15.0 | 7.1 | |
| | | | *Platycarya strobilacea* | 4 | 12.0 | 27.0 | 7.1 | |
| | | SC | *Quercus serrata* | 19 | 6.0 | 5.0 | 34.0 | |
| | | | *Quercus mongolica* Fish. ex Ledeb | 2 | 6.0 | 9.0 | 3.6 | |
| | | | *Ulmus davidiana* var. *japonica* | 1 | 6.0 | 9.0 | 1.8 | |
| | | SL | *Quercus serrata* | 1 | 2.0 | 0.1 | 1.8 | |
| | SF | TC | *Quercus variabilis* | - | 11.5 | 77.0 | - | Wooseong mountain in Doryong-dong, Yuseong-gu, Daejeon |
| | | SC | *Styrax japonicus* | - | 7.2 | 4.0 | - | |
| | | SL | *Lindera obtusiloba* | - | 2.4 | 5.0 | - | |
| | RF | TC | *Quercus variabilis* | 32 | 8.0 | 17.0 | 28.6 | Ecological forest situated in National Institute of Ecology at 1210, Guemgang-ro, Maseo-myeon, Seocheon-gun, Chungcheongnam-do |
| | | | *Quercus aliena* Blume | 11 | 8.0 | 15.0 | 9.8 | |
| | | | *Platycarya strobilacea* | 6 | 8.0 | 12.0 | 5.4 | |
| | | | *Quercus serrata* | 26 | 8.0 | 11.0 | 23.2 | |
| | | SC | *Quercus aliena* Blume | 2 | 2.5 | 9.5 | 1.8 | |
| | | | *Quercus variabilis* | 2 | 2.5 | 9.5 | 1.8 | |
| | | | *Quercus mongolica* Fisch. ex Ledeb. | 4 | 2.5 | 9.5 | 3.6 | |
| | | | *Quercus serrata* | 6 | 2.5 | 9.5 | 5.4 | |
| | | SL | *Lespedeza maximowiczii* | 18 | 0.5 | 0.4 | 16.1 | |
| | | | *Lindera obtusiloba* | 2 | 0.5 | 0.4 | 1.8 | |
| | | | *Corylus heterophylla* Fisch. ex Trautv. | 1 | 0.5 | 0.4 | 0.9 | |
| | | | *Symplocos chinensis* f. *pilosa* | 1 | 0.5 | 0.4 | 0.9 | |
| | | | *Zanthoxylum schinifolium* S. et Z. | 1 | 0.5 | 0.4 | 0.9 | |
| | PF | TC | *Quercus variabilis* | - | 9.8 | 20.0 | - | Restored Quercus forest situated in the restored park at 910 Dunsan-dong, Seo-gu, |
| | | SC | *Quercus aliena* Blume | - | 6.1 | 44.0 | - | |
| | | SL | *Quercus acutissima* | - | 2.8 | 7.0 | - | |

[1] TC, top canopy; SC, sub-canopy; SL, shrub layer; [2] CF, Climax Forest; SF, Secondary Forest; RF, Restored Forest; PF, Planted Forest in the restored park.

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