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Coarse Woody Debris Dynamics in Relation to Disturbances in Korea's Odaesan National Park Cool-Temperate Forests

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Abstract: Coarse woody debris (CWD) has historically been extensively utilized in Korea, with significant accumulation occurring mainly after the establishment of protected areas. This study, conducted in Odaesan National Park (designated in 1975), investigated the distribution and characteristics of CWD across five forest types with permanent plots. It also examined the effects of human and natural disturbances on CWD dynamics and evaluated its role in carbon storage. CWD mass varied significantly, ranging from 0.7 Mg ha^{-1} in *Pinus-Quercus* (PQ) forests to 31.9 Mg ha^{-1} in Broadleaved–*Abies* (BA) forests. The impacts of disturbances shifted markedly before and after the park's designation; prior to this, human activities such as logging substantially affected BA, PQ, and *Prunus-Salix* (PS) forests, while *Quercus-Tilia* (QT) forests were primarily impacted by wildfires. After designation, natural disturbances became the primary contributors to CWD accumulation, with a major windstorm in BA forests adding 12.09 Mg ha^{-1} of CWD (37.8% of the total). Late-successional forests exhibited higher CWD mass, advanced decay stages, and greater diversity, as well as elevated CWD-to-carbon storage ratios, highlighting their role as crucial carbon reservoirs. In light of climate change, these findings emphasize the need for forest management practices that enhance CWD's contributions to biodiversity conservation and carbon storage.

Keywords: anthropogenic disturbance; disturbance history; forest ecosystem; forest succession; national park; protected area

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1. Introduction

Woody plants provide consistent organic matter to forests through leaves, fallen branches, bark, and seeds. When a tree dies, it reintegrates into the ecosystem as coarse woody debris (CWD), which exists as snags (standing dead trees), logs (fallen trunks and branches), or stumps (bases of broken trees). CWD originates from both natural processes, such as aging, succession, competition, and environmental stressors like wind, snow, fire, pests, and diseases, as well as from human activities like logging [1]. It influences forest development and ecosystem dynamics until it is fully decomposed [2,3]. Studies on forest ecosystems have demonstrated that coarse woody debris (CWD) is a crucial element, vital for maintaining the health and sustainability of the ecosystem [1,4].

Nevertheless, CWD has historically been regarded as a source of diseases, pests, and fires [4]. This led to a lack of understanding of its role in forest ecosystems. Additionally, past forest management practices such as logging significantly affected CWD dynamics. Removing and harvesting old trees, a potential source of CWD, reduced CWD amounts [5]. The amount of CWD in managed forests was only about 2 to 30% of that in unmanaged forests [6].

CWD contributes to ecosystem function in several ways. It serves as a seed germination site (e.g., [1,7]), a water reservoir during drought (e.g., [3,8]), and a habitat for many forest animals (e.g., [1,9,10]) and microorganisms [11]. CWD is also important for maintaining energy flow and nutrient cycling in forest ecosystems. This is because it is the primary energy source for decomposers. Its decomposition can lead to a gradual release of carbon, nitrogen, phosphorus, and other nutrients [12]. Thus, it promotes soil fertility and productivity (e.g., [13]), supports forest recovery and natural regeneration, protects ecosystems from disturbances associated with nutrient loss, and improves forest ecosystem diversity and stability [14].

In addition to its ecological roles, CWD serves as a significant long-term carbon storage component within forest ecosystems [15,16]. Studies have shown that CWD accumulates carbon over extended periods, particularly in late-successional forests, where larger, more decayed wood decomposes at a slower rate, thereby contributing to long-term carbon sequestration. This relationship between forest succession stages and CWD highlights that early-successional forests, impacted by recent disturbances, generally contain less CWD, while late-successional forests tend to accumulate more diverse and advanced decay classes of CWD [17,18]. Understanding the interaction between succession stages and CWD dynamics is therefore crucial for assessing forest carbon storage capacities and developing conservation strategies.

Forest succession, disturbance history, land use patterns, and habitat heterogeneity all influence the size distribution, amount, and nutrient content (carbon and nitrogen concentrations) of CWD across different decay classes [19]. Additionally, characteristics of tree species—such as maximum height, diameter, density, and decay rate—also affect the quantity of CWD in forests [20]. These factors provide valuable information about the structural and functional components of forest ecosystems [21]. As such, CWD is often used as an index to reflect the historical development of forest communities (e.g., [22–24]).

Understanding the size, age composition, structure, and distribution patterns of dead trees can offer insights into stand dynamics and the mechanisms that maintain species in an ecosystem [21]. Furthermore, the characteristics of CWD are crucial for preserving biological diversity in forests [25,26]. For example, the diameter and size of CWD significantly influence its suitability as a habitat for various faunal species [26,27].

Korea has maintained a high population density throughout its long history. Most regions experience a cool-temperate climate, with cold and long winters. As a result of overexploitation, primarily for fuel, forests were severely degraded until the 1970s [28]. Therefore, except for areas that were difficult for people to access, such as high mountains or remote areas, or places considered sacred (e.g., around temples), it was difficult for CWD to remain in forests. Fortunately, with the transition to alternative fuel sources and economic growth, forest use has decreased, allowing forests to naturally recover. Since the late 1970s, studies on CWD have been conducted in several countries [29,30]. However, in Korea, it was only recently that the importance of CWD was recognized, resulting in a limited number of published studies [25,31–33].

Odaesan National Park spans a wide elevation range, reaching a peak of 1563 m, and is characterized by complex terrain and a diverse history of land use. Since its designation as a national park in 1975, it has been actively protected from anthropogenic disturbances. In areas below 800 m in elevation, early-successional *Pinus densiflora* forests have developed [34]. At higher elevations, a patchwork of mid-successional oak forests and late-successional broadleaf mixed forests can be found, depending on the type and intensity of past disturbances. The presence of an ancient temple within the park has contributed to the preservation of the surrounding forests, which are regarded as sacred. Consequently, even before the designation of the national park, the forests around the temple benefited from protection.

This study was conducted in five forests in Odaesan National Park, where permanent plots were established to examine the succession of existing vegetation: *Pinus-Quercus* forest, *Quercus-Tilia* forest, *Populus-Salix* forest, Broadleaved–*Abies* forest, and Subalpine forest [34]. These forests differ in terms of topography, particularly elevation, and successional stages (based on stand structure and species composition). These forests not only represent characteristic forest types of the park landscape but are also widely distributed across other regions in Korea's cool-temperate zones, except for the Subalpine forest.

Within these permanent research plots, our objectives were as follows: first, to assess the distribution and characteristics of coarse woody debris (CWD); second, to distinguish between anthropogenic and natural disturbances before and after the national park's designation as a protected area, and to examine their impact on CWD dynamics; third, to analyze the relationship between CWD distribution and the status of existing forests, including abundance and successional stages; and, finally, to estimate the carbon stocks of the current forests and CWD.

2. Materials and Methods

2.1. Study Region

Odaesan National Park lies between 37°45′ and 37°50′ N and 128°30′ and 128°40′ E. This study covered five forest types characteristic of Odaesan National Park's landscape under a cool-temperate climate, with long-term monitoring plots established: *Pinus-Quercus* forest (PQ), *Quercus-Tilia* forest (QT), *Populus-Salix* forest (PS), Broadleaved–*Abies* forest (BA), and Subalpine forest (SA). Given the topographic conditions (primarily elevation), we analyzed the five study forests as belonging to three different successional pathways [34]: low zone (around 400 m, PQ), middle zone (around 800–1000 m, QT, PS, BA), and subalpine zone (around 1500 m, SA) [34].

Differences in topography and varied histories of both human and natural disturbances have resulted in distinct stand ages and species compositions among these forests. Based on ten years of data, we assessed PQ in the low zone as representing the pioneer stage, QT and PS in the middle zone as intermediate stages, BA in the middle zone as the late stage, and SA in the subalpine zone as the late but fluctuating stage. For detailed information on permanent plots and the vegetation structure of these forests, refer to [34].

2.2. CWD Distribution Survey, Classification, and Decay Assessment

To survey CWD distribution and perform classification and decay assessment, we examined coarse woody debris (CWD) across 69 permanent plots (20×20 m^2) in 2008. These plots had originally been established in 2005 to study vegetation structure and succession in these forests. Of the 69 plots, 50 (totaling 2 ha) were located in BA as the representative mature forest of this landscape. The remaining plots were distributed as follows: 7 in QT, 6 in PS, and 3 each in PQ and SA. We defined CWD as dead woody material with a diameter of at least 10 cm [35]. The shape of CWD was categorized as one of three types [4]: snag (standing dead, DBH $\geq$ 10 cm, height $\geq$ 1 m, and lean angle $\geq$ 45°), log (fallen, diameter $\geq$ 10 cm, length $\geq$ 1 m, and lean angle $<$ 45°), and stump (top diameter $\geq$ 10 cm and height $<$ 1 m). Causes of tree mortality were categorized as logging (showing signs of human cutting), windstorm (documented in permanent plots with precise records), and natural death (Figure 1).

Because the precise death timing of each CWD piece was unknown, decay duration could not be directly measured. Instead, decomposition progress was assessed using a 'decay class' system [36,37]. Uniform application of decay classes can be difficult as decomposition rates vary with species and environmental conditions, so decay classes should generally reflect consistent decomposition patterns and density reductions over time [30].

This study adapted the decay class system outlined in [38,39] (Figure 2). The same decay classes were applied to snags and logs, as they decayed at similar rates. However, stumps were classified separately, as they decay faster: we assigned them to decay class 4, following [38]. In *Carpinus cordata*, bark persisted even with severe wood decay, so bark presence was excluded as a decay class factor. In *Abies holophylla* and *Betula schmidtii*, sapwood stayed firm while heartwood fully decayed and became hollow [33]. Consequently, decayed wood was classified as class 4 with heartwood and class 5 if hollow. We conducted a preliminary sampling in August 2007. During the main survey in 2008, we were able to observe the changes, which led us to conclude that this classification of decay could be applied.

Figure 1. Stump cut by logging (**left**) and tree uprooted by the windstorm in 2006 (**right**).

Figure 2. Examples of decay class (**1** to **5**) for *Acer pseudo-sieboldianum* logs.

2.3. Assessment of CWD Quantity, Diversity, Biomass, and Carbon Storage

The quantity of CWD was determined by calculating its volume and multiplying it by its density. Volume was measured using a fixed-area sampling method across permanent plots. For each CWD piece with a diameter exceeding 10 cm, the location, cross-sectional area, and length were measured. CWD shape types—snags, logs, and stumps—were recorded separately, as each type has unique volume estimation requirements (snag: [40], log: [3], stump: [38]). A tree height meter (Vertex III Hypsometer, Haglof Inc. Långsele, Sweden) was used to measure the height of snags.

CWD samples were collected as disks with a minimum thickness of 5 cm. Sample density was calculated by dividing the dry weight by its volume. Volume was calculated based on sample type using the formula outlined by [41], and dry weight was determined by drying the samples at 80 °C for seven days.

To evaluate CWD diversity per plot, we used the Siitonen Index [42], which counts the variety of distinct deadwood types that provide habitats for species with different niches. In our study, the Siitonen Index was determined based on three CWD types (1: snag, 2: log, 3: stump), three diameter classes (class 1: small, 10–20 cm; class 2: medium, 20–30 cm; class 3: large, $\geq$40 cm), and three decay states (1: fresh, decay class 1; 2: moderate, decay classes 2 and 3; 3: rotten, decay classes 4 and 5). Consequently, CWD diversity (Siitonen Index) for each plot ranged from 0 (no CWD) to 9 (all types, diameters, and decay states of CWD present) [43].

We estimated biomass and carbon storage for living trees (DBH $\geq$ 10 cm). Biomass for live trees was calculated using allometric equations based on DBH values, obtained from permanent plot data from 2005 and 2015 [34]. Primarily, national standard biomass allometric equations for Korea were used, and in cases where no species-specific equations were available, we applied the equations used by the Korea National Park Research Institute [44]. When species-level equations were not applicable, we used genus- or family-level equations. Carbon storage for dead trees was estimated by multiplying the biomass value by a carbon content ratio of 0.5 [44].

2.4. Statistical Analysis

All statistical analyses were performed using SYSTAT software v. 13. Descriptive statistics summarized the data, and correlation analyses examined relationships between

CWD characteristics, living tree biomass, and forest succession stages. Hypothesis testing was carried out using *t*-tests, with statistical significance determined at $p < 0.05$.

3. Results

Distribution Characteristics of CWD

CWD was highest in the BA (31.93 Mg ha^{-1}) and lowest in the PQ (0.70 Mg ha^{-1}) (Table 1). Logging-related CWD was most abundant in BA, with no logging traces detected in QT and SA. Although identifying the specific species of CWD with logging traces in BA was challenging, we inferred that they were either *Abies holophylla* or *Betula schmidtii* by comparing them with nearby woody plants. These species were commonly preferred for various uses at that time. Meanwhile, a windstorm in 2006 was a singular event that led to the death of 12.09 Mg ha^{-1} of trees, comprising 37.8% of the current CWD in BA (Table 1). The windstorm primarily impacted *Abies holophylla* and *Abies nephrolepis*, with the former experiencing the most significant loss in basal area and the latter in stem numbers due to uprooting.

Table 1. Total CWD mass (Mg ha^{-1}) by cause of tree death in five forest types (2008 data).

Cause of Death	*Pinus-Quercus* (PQ)	*Quercus-Tilia* (QT)	*Populus-Salix* (PS)	Broadleaved–*Abies* (BA)	Subalpine (SA)
Logging	0.01 (1.9)	-	0.01 (0.1)	5.42 (17.0)	-
Windthrow in 2006	-	-	-	12.09 (37.8)	-
Natural death	0.69 (98.1)	5.99 (100)	7.51 (99.9)	14.43 (45.2)	7.43 (100)
Total	0.70	5.99	7.52	31.93	7.43

Values in parenthesis indicate the percentage of CWD mass in each forest.

In BA, 29.6% of the unidentified CWD was attributed to logging, representing 99.2% of the total CWD formed by logging. Among the three CWD types, 83% of all snags resulted from natural death, 44% of all logs from natural death and 40.6% from windstorm damage, while 80.8% of all stumps were attributed to logging.

The composition of CWD in PS and SA had the highest proportions of snags, at 55.2% and 65.5%, respectively. Higher log proportions were found in PQ and BA, at 75.8% and 91.6%, respectively (Figure 3). BA contained a greater mass of logs compared to other types, even when excluding logs produced by the 2006 windstorm. Analysis of CWD species composition showed that the dominant species in PQ and QT were also most commonly found as CWD in their respective forests. *Pinus densiflora* was the predominant CWD species in PQ, making up 47.7% of the total, while *Quercus mongolica* was the predominant CWD species in QT, making up 49.9% of the total. Unidentified CWD species were found in BA, PS, and SA, accounting for 57.0%, 56.0%, and 44.3% of the total in each respective forest. The high species richness and presence of advanced decay stages complicated species identification.

CWD with a diameter of less than 20 cm was most abundant across all forest types, displaying an inverted J-shape distribution as the numbers decreased with increasing diameter. In PQ, all CWD diameters were under 20 cm. In QT and PS, CWD with a diameter of less than 20 cm was the most prevalent. All CWD in SA ranged from 10 to 40 cm in diameter. In contrast, in BA, CWD with a diameter of 70–80 cm was most common, accounting for 21.6% (6.9 Mg ha^{-1}) of the total, followed by CWD in the 40–50 cm (5.1 Mg ha^{-1}) and 50–60 cm (5.1 Mg ha^{-1}) diameter classes. Most of the CWD in the larger diameter classes resulted from windstorm damage, including uprooted *Abies holophylla* trees [45]. CWD with logging traces ranged in diameter from 30 to 60 cm. Diameter distributions by CWD type indicated that the frequency of snags and logs decreased with increasing diameter. However, for stumps, those with diameters of 10–20 cm were most frequent (27.6%), followed by those with diameters of 50–60 cm (21.8%).

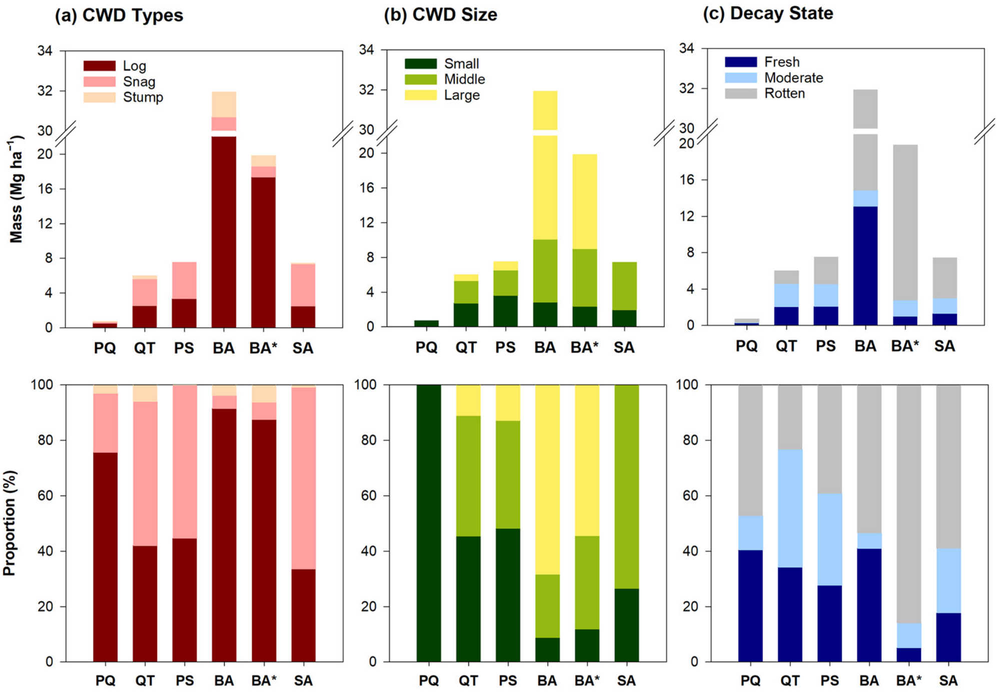

Figure 3. Types, size, and decay state of CWD across five forest types in 2008. BA* is the value of BA's CWD mass excluding the CWD caused by the 2006 strong windstorm. PQ: *Pinus-Quercus* forest, QT: *Quercus-Tilia* forest, BA: Broadleaved–*Abies* mixed forest, PS: *Populus-Salix* forest, SA: Subalpine forest.

The decay classes of CWD indicate that in PQ, there were no class 1 snags, with class 2 snags being the most common, while the highest proportion of logs were class 1 and there were no class 2 logs (Table 2). In QT, snags were predominantly class 2, and logs were predominantly class 3. In BA, class 1 was the most common decay class, representing 41.7% (12.2 Mg ha^{-1}) of the total, followed by class 5 at 34.9% (10.2 Mg ha^{-1}). Most of the class 1 CWD resulted from a strong windstorm. Excluding class 1, class 5 was the most prevalent overall. Among snags, class 1 was the most common, primarily consisting of stems with broken tops caused by the windstorm. Classes 3 and 4 accounted for 98.9% of stumps, which were mainly a result of past logging.

We examined the relationship between CWD mass and forest structural variables (density, basal area, and biomass) using permanent plot data from 2005 and 2015. Although the correlations were not statistically significant, CWD quantity and diversity generally increased in late-successional forests (Figure 4). The low CWD mass observed in the SA forests, despite being in a late-successional stage, is likely due to their location in the subalpine zone.

The carbon storage of CWD and existing forests was calculated (Figure 5). Aboveground carbon stocks varied by forest type, with the highest total carbon storage observed in QT. However, the proportion of CWD in total carbon storage was greater in late-successional forests. Over the decade from 2005 to 2015, biomass accumulation was higher in the early-successional forest than in the late-successional forest (Figure 6). Although biomass increased substantially in the early-stage forest, the amount of dead trees remained lower than in the late-stage forest, resulting in a lower ratio of CWD carbon storage to total carbon storage compared to that of late-stage forests.

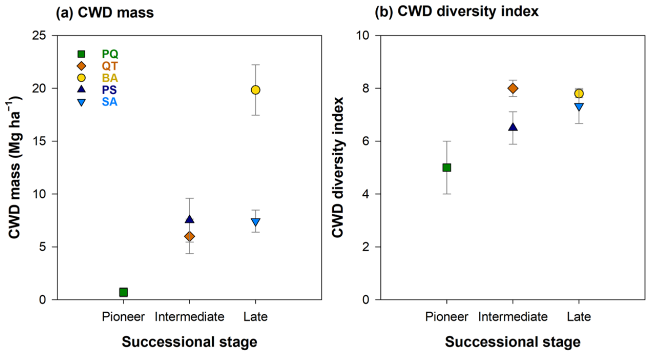

Figure 4. CWD mass (**a**) and CWD diversity index (**b**) according to forest succession stage. PQ: *Pinus-Quercus* forest, QT: *Quercus-Tilia* forest, BA: Broadleaved–*Abies* mixed forest, PS: *Populus-Salix* forest, SA: Subalpine forest.

Table 2. CWD mass (Mg ha^{-1}) and density (No. ha^{-1}) for decay class across five forest types in 2008. PQ: *Pinus-Quercus* forest, QT: *Quercus-Tilia* forest, BA: Broadleaved–*Abies* mixed forest, PS: *Populus-Salix* forest, SA: Subalpine forest.

CWD Type	Decay Class	PQ	QT	PS	BA	SA
snag	1	-	0.68 (21)	0.78 (29)	0.56 (6)	1.26 (33)
	2	0.11 (17)	1.34 (29)	1.29 (42)	0.19 (8)	0.03 (8)
	3	-	0.88 (29)	1.49 (29)	0.38 (11)	1.16 (58)
	4	-	0.06 (7)	0.59 (17)	0.10 (6)	1.60 (42)
	5	0.04 (8)	0.16 (4)	-	0.23 (7)	0.82 (25)
	Total	0.15 (25)	3.12 (89)	4.15 (117)	1.45 (36)	4.87 (167)
log	1	0.17 (17)	-	-	12.18 (26)	-
	2	-	0.03 (4)	-	0.16 (11)	0.02 (8)
	3	0.07 (8)	1.42 (61)	1.00 (38)	1.33 (51)	0.52 (33)
	4	0.14 (17)	0.77 (39)	1.24 (50)	5.37 (118)	1.70 (33)
	5	0.15 (25)	0.30 (18)	1.12 (46)	10.20 (130)	0.25 (8)
	Total	0.53 (67)	2.52 (121)	3.36 (133)	29.24 (335)	2.50 (83)
stump	1	-	-	-	0.01 (1)	-
	2	-	-	0.01 (8)	0.01 (3)	-
	3	0.02 (17)	0.26 (14)	-	0.05 (7)	0.05 (8)
	4	0.01 (8)	0.10 (29)	-	1.17 (33)	0.02 (8)
	Total	0.02 (25)	0.36 (43)	0.01 (8)	1.24 (44)	0.06 (17)
Total		0.70 (117)	5.99 (254)	7.52 (258)	31.93 (414)	7.43 (267)

Values in parenthesis indicate the amount of CWD per ha. 3.2. CWD Composition and Carbon Storage

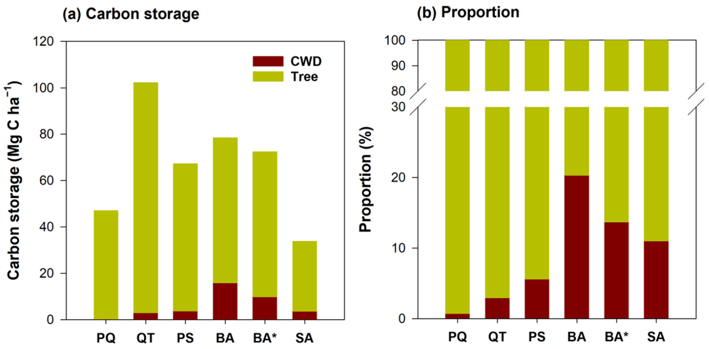

Figure 5. Carbon storage of the forest living trees and CWD (Mg ha^{-1}) (**a**) and their proportion (**b**) by forest type. BA* is the value of BA's CWD mass excluding the CWD caused by the 2006 strong windstorm. PQ: *Pinus-Quercus* forest, QT: *Quercus-Tilia* forest, BA: Broadleaved–*Abies* mixed forest, PS: *Populus-Salix* forest, SA: Subalpine forest.

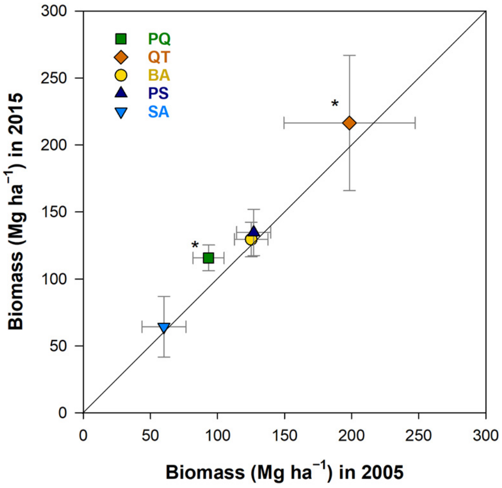

Figure 6. Plot-level biomass changes (DBH ≥ 10 cm) over a ten-year period (2005–2015). PQ: *Pinus-Quercus* forest, QT: *Quercus-Tilia* forest, BA: Broadleaved–*Abies* mixed forest, PS: *Populus-Salix* forest, SA: Subalpine forest. A paired *t*-test was performed between the start and end of the 10-year interval within a forest type at * $p < 0.05$.

4. Discussion

The most recent data indicated that South Korea's average growing stock was 157.8 m^3 ha^{-1} in 2018 [46]. However, in 1960, 42% (2.2 million ha) of the country's forest area was unstocked, with 19% (0.52 million ha) of this area completely denuded [47]. In 1972, the average growing stock was only 10.9 m^3 ha^{-1} [47,48]. This forest devastation likely resulted from overexploitation for fuelwood due to factors like high population density, a long human history, and cold winters, rather than solely from events like Japanese colonial exploitation or the Korean War [28,49]. In these challenging circumstances, dependence on forests for fuel, timber, and food was inevitable [50]. Dead trees and forest litter were fully utilized, as they provided vital sources of fuel and compost.

4.1. Distribution Characteristics of CWD Across Five Forests

The distribution of CWD on Odaesan Mountain varied considerably based on forest type. In PQ, the total amount of CWD was the lowest (0.70 Mg ha^{-1}) and comprised small-sized logs. The basal area of this forest type (around 25.6 m^2 ha^{-1}) was higher than that of PS and SA [34]. Despite this, the significantly lower CWD amount suggests past disturbances may have occurred.

In QT and PS, the amounts of CWD were 5.99 and 7.51 Mg ha^{-1}, respectively, with PS showing about 25% higher CWD. Both forest types had similar proportions of CWD types (snags and logs) and sizes (small and medium), though a greater portion of CWD in PS was in a rotten stage. In contrast, BA had a significantly higher amount of CWD at 31.93 Mg ha^{-1} than other forests. Of this, 12.09 Mg ha^{-1} was produced by a one-time event, the 2006 windstorm (classified as decay class 1 logs). Excluding this event, 19.84 Mg ha^{-1} of CWD predated the storm. The CWD pattern in BA also differed from that of other forests: prior to the windstorm, there were many large-sized logs, and aside from the newly formed CWD in the fresh stage, the proportion in the rotten stage was substantial. Additionally, many stumps were in decay classes 3 and 4, while stumps in classes 1 and 2 were scarce. In SA, the CWD amount was 7.43 Mg ha^{-1}. Compared to other forests, it had a higher number of medium-sized snags, and the proportion of CWD in a decayed state was the highest among the forests.

Comparable data on CWD amounts from other Korean studies are limited. In an old-growth *Quercus-Carpinus* forest in Gwangneung, CWD was reported to be 15.9–20.1 Mg ha^{-1} [51] and 5.6–17.6 Mg ha^{-1} [31]. This forest has been preserved for approximately 500 years due to its proximity to a royal tomb. In *Quercus-Acer* forests

(150–200 years) on Mt. Jeombong, CWD mass ranged from 22.2 to 24.5 Mg ha^{-1} [51]. Although BA shares a similar stand age and species composition with these forests, the higher dominance of *Abies holophylla* in BA may contribute to the greater CWD amount found here.

In the intact temperate forests of North America, CWD mass varies from 6 to 269 Mg ha^{-1} depending on forest type [1]. Generally, broadleaved forests (11–38 Mg ha^{-1}) tend to accumulate less CWD than coniferous forests (10–511 Mg ha^{-1}) [1]. Except for BA, the CWD amounts across the five forests in this study fell closer to the lower end of this range. Although factors like stand age, forest type, successional stage, decay rate, and topography all influence CWD amounts, natural or human disturbances are considered major contributors [51].

4.2. Effects of Disturbances on CWD Distribution Across Five Forests

The low CWD mass in PQ forests likely results from past CWD removal, as these low-elevation areas are accessible to humans and were historically used for firewood, impacting CWD levels [20]. The mild maritime climate may also accelerate decomposition here, though human use is a primary factor. These early-successional forests, disturbed recently, likely experienced CWD removal even after the park's 1975 designation.

In QT forests, the structure shows recovery from a past fire, with dominant *Quercus* trees resprouting in a clump shape [52]. Fire-damaged trees were probably removed over a century ago, with significant CWD accumulation starting only after park designation. The high density of live and dead stems suggests density-dependent thinning among *Quercus mongolica* [34]. PS forests, adjacent to a valley, show signs of past logging, though natural disturbances like summer floods now contribute dead trees, which may be transported by water flow.

BA forests contain numerous stumps with cutting traces in advanced decay [38,53], suggesting selective logging before park designation. In contrast, the absence of cut marks on stumps in decay classes 1 and 2 indicates no human disturbance since that time. However, a major windstorm in 2006 with heavy rain caused shallow-rooted, tall conifers such as *Abies holophylla* and *Abies nephrolepis* to be uprooted, and species like *Tilia amurensis* to snap [45]. This single event contributed 12.09 Mg ha^{-1}, or 37.9%, of the total CWD, resulting in a significant portion of large, newly fallen logs in decay class 1. Given the dominance of wind-prone *Abies* trees and the presence of large, heavily decayed logs, it is likely that windstorm damage also occurred in the past.

SA forests, in high-elevation subalpine zones, are less accessible and show no human disturbance but experience natural disturbances from snowstorms, wind, and cold. Here, *Abies nephrolepis* accounts for much of the CWD.

Overall, CWD dynamics in these forests reflect different disturbance histories. Before park designation, logging, fire, and CWD removal shaped forest composition. Since designation, natural disturbances like windstorms (BA), floods (PS), and environmental stress (SA) have been primary influences.

4.3. Relationship Between CWD and Existing Forests

Studies in European-beech-dominated forest reserves reveal that CWD amounts vary substantially, influenced by factors such as forest type, time since reserve establishment, and the quantity of live trees [54]. In our analysis, we examined the relationship between CWD mass and forest structural variables (density, basal area, and biomass) but found no significant correlation, likely due to variations in disturbance types and intensities across forest types as well as the removal of CWD. This aligns with other research indicating that CWD density and volume are only weakly correlated with the structure of living trees, with mean tree diameter showing the strongest relationship to CWD volume [20].

While the quantitative aspects of CWD dynamics are relatively well understood, its diversity dynamics—related to tree species, size, and decay status—are less studied. CWD diversity can significantly enhance habitat heterogeneity and, in turn, species diversity [55].

In general, factors like time since disturbance (TSD), upper layer type, and stand origin strongly influence CWD diversity, although no direct relationship between CWD diversity and species diversity was observed; species diversity is affected by a combination of stand age, species composition, disturbances, and environmental factors. Nonetheless, late-stage forests consistently exhibited greater CWD mass and diversity than early-stage forests.

In tropical forests, alpha diversity increases with succession, with old-growth forests showing significantly higher CWD diversity than younger ones [43]. This suggests that CWD assessments in tropical forests can serve as useful indicators for identifying conservation areas and evaluating biodiversity credits. Another study [26] underscores the importance of CWD diversity in maintaining forest biodiversity, finding that CWD decay stages are associated with factors such as woody plant density, height, and species composition. The study highlights that a diversity of CWD quantities and decay stages should be maintained to support native forest diversity.

4.4. Role of CWD in Carbon Reserves and Forest Management Practices

CWD plays an essential, yet often underestimated, role in long-term forest carbon storage [56]. Studies of carbon reserves in deciduous afforestation areas in northeastern China show a steady increase in carbon storage with stand age, reflecting a sigmoid trend similar to that observed in tree biomass as trees mature. Mature stands accumulate more CWD than younger stands, and CWD carbon storage is closely linked to site productivity [57]. Notably, CWD makes up a substantial portion of total forest carbon, decomposing much more slowly than leaf litter and sequestering carbon over extended periods. This study also found that CWD carbon storage ratios are higher in late-successional forests, where slower growth rates and accumulated dead wood contribute to enhanced carbon storage.

Although younger forests sequester carbon at a faster rate, older forests achieve higher overall carbon storage due to accumulated dead wood and reduced decomposition rates. This challenges the misconception that replacing old forests with younger ones will increase carbon sequestration, as it overlooks the critical role of dead trees in carbon storage and the additional biodiversity benefits they provide.

Dead trees are vital for biodiversity, especially in high-altitude and temperate forests, where they serve as key biodiversity indicators [6]. CWD volume in managed forests is a critical metric for assessing sustainability and biodiversity conservation. For this reason, Europe uses CWD levels as one of nine indicators of sustainable forest management (Criterion 4) [54,58]. However, current forest management often results in low CWD stocks. Trees in poor health or nearing senescence, which could contribute to future CWD, are frequently removed, and CWD itself is often cleared during harvesting operations [59]. In Korea, dead trees are rare outside protected areas due to forest management practices that prioritize timber production, with trees generally removed at the final cutting age. Additionally, post-fire deadwood removal is practiced to prevent pine wilt disease and improve forest esthetics.

Old-growth forests consistently have higher CWD values across all variables compared to managed forests, emphasizing the importance of CWD in these ecosystems [42]. Large-diameter logs, as one of the slowest-recovering elements in forest structure, can take centuries to fully recover, highlighting the value of preserving natural forests to maintain both CWD's structural and functional integrity [56]. Thus, CWD is a crucial element for both biodiversity conservation and carbon storage, necessitating forest management practices that acknowledge and protect these roles.

5. Conclusions

In the forests of Odaesan National Park, the distribution and quantity of coarse woody debris (CWD) are largely shaped by historical human activities and ongoing natural disturbances. Since the establishment of protected areas, human exploitation and disturbances have been largely curtailed, allowing natural disturbances to become the primary drivers of CWD accumulation. Events such as windstorms in Broadleaved–*Abies* forests and snowstorms in high-elevation Subalpine forests are key contributors to this process.

CWD plays a vital role in enhancing carbon storage, especially in late-successional forests, where its slow decay functions as a long-term carbon reservoir. Additionally, deadwood serves as an important biodiversity indicator. However, current forest management practices often result in reduced CWD levels, potentially undermining long-term ecological functions and carbon storage capabilities. In South Korea, deadwood is scarce outside protected areas due to the focus on timber production.

Given the growing impact of climate change, the ecological and carbon storage value of CWD is expected to become increasingly important. Therefore, forest management strategies must be adjusted to support and enhance these critical functions.

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