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Assessment of Deadwood and Natural Regeneration in a Protected Lowland Forest of Northern Iran

Untersuchungen zu Totholz und natürlicher Verjüngung in einem geschützten Tieflandwald im Norden des Iran

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Schlüsselbegriffe: Zersetzungsklassen, Zerfall, Waldbewirtschaftung, *Parrotia persica*, *Carpinus betulus*, Jungwuchs, stehendes Totholz

Abstract

Awareness of the ecological importance of deadwood as a key structural component of forest ecosystems is steadily increasing. Consequently, forest managers' acceptance of deadwood retention in managed forests is becoming more frequent. This study investigates the quantitative and qualitative characteristics of deadwood and natural regeneration within a 25-hectare protected lowland forest located in northern Iran. On three transects measuring 50 m × 750 m all types of deadwood, that is, snags, logs, and stumps, were recorded. Each deadwood item was classified by decay stage (classes 1 to 4) and tree and shrub species was identified. 1000 m² sample plots on a grid system of 150 m × 200 m were established to examine forest structure. Within each 1000 m² sample plot, four subplots measuring 5 m × 4 m were placed at the inner corners to record natural regeneration, taking into account species and growth

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stage. Our results show, that *Carpinus betulus* represent the highest number and volume of deadwood. The total deadwood volume was on average 9.8 m^3/ha, representing 4.9% of the volume of living trees. Among the three deadwood types, logs had the highest volume at 6.8 m^3/ha. The majority of deadwood occurred in the more advanced decay classes (Classes 3 and 4), while the lowest frequency and volume were recorded in the least decayed class (Class 1). Total natural regeneration was 1,593 individuals per hectare, with 1,038 per hectare and 501 per hectare in the sapling and thicket stages, respectively. *Parrotia persica* was most frequent in the natural regeneration, but its share was not significantly different from that of *Carpinus betulus*. For both species, regeneration was most abundant at the seedling stage compared to the sapling and thicket stages. The abundance of deadwood, the composition of tree and shrub species, and the degree of decay may significantly influence forest structure and the establishment of natural regeneration. It is recommended that the management of such protected forests not only focus on stand structure and volume accumulation, but also consider species admixture regulation, the promotion of natural regeneration, and the preservation and appropriate spatial distribution of deadwood across the landscape.

Zusammenfassung

Das Bewusstsein für die ökologische Bedeutung von Totholz als zentralem Strukturbestandteil von Waldökosystemen nimmt stetig zu. In Folge steigt die Bereitschaft von Waldbewirtschafter/innen zum Erhalt von Totholz in bewirtschafteten Wäldern. Diese Studie untersucht die quantitativen und qualitativen Merkmale von Totholz und natürlicher Verjüngung in einem 25 Hektar großen, geschützten Tieflandwald im Norden des Iran. Auf drei Transekten mit den Abmessungen 50 m × 750 m wurden alle Arten von Totholz, d. h. Totholzstümpfe, liegende Stämme und Baumstümpfe, erfasst. Jedes Totholzstück wurde nach Zerfallsklassen (Klassen 1 bis 4) klassifiziert und die Baum- und Strauchart wurden bestimmt. Zur Untersuchung der Waldstruktur wurden 1000 m^2 große Probeflächen auf einem Raster von 150 m × 200 m angelegt. Innerhalb jeder 1000 m^2 großen Probefläche wurden an den inneren Ecken vier 5 m × 4 m große Unterflächen angelegt, um die natürliche Verjüngung unter Berücksichtigung von Art und Wachstumsstadium zu erfassen. Unsere Ergebnisse zeigen, dass *Carpinus betulus* die höchste Anzahl und das höchste Volumen an Totholz aufweist. Das gesamte Totholzvolumen betrug durchschnittlich 9.8 m^3/ha und entspricht 4.9 % des Volumens lebender Bäume. Von den drei Totholzarten hatten Baumstämme mit 6.8 m^3/ha das höchste Volumen. Der Großteil des Totholzes trat in den fortgeschritteneren Zerfallsklassen (Klassen 3 und 4) auf, während die geringste Häufigkeit und das geringste Volumen in der am wenigsten zerfallenen Klasse (Klasse 1) verzeichnet wurden. Die gesamte natürliche Verjüngung betrug 1593 Individuen pro Hektar, davon 1038 pro Hektar und 501 pro Hektar im Jungbaum- und Dickungsstadium. *Parrotia persica* kam in der natürlichen Verjüngung am häufigsten vor, ihr Anteil

unterschied sich jedoch nicht signifikant von dem von *Carpinus betulus*. Bei beiden Arten war die Verjüngung im Jungbaumstadium im Vergleich zum Jungbaum- und Dickungsstadium am stärksten. Der Totholzreichtum, die Zusammensetzung der Baum- und Straucharten sowie der Verfallsgrad können die Waldstruktur und die Entstehung der natürlichen Verjüngung maßgeblich beeinflussen. Es wird empfohlen, dass sich die Bewirtschaftung solcher Schutzwälder nicht nur auf Bestandesstruktur und Volumenakkumulation konzentriert, sondern auch die Regulierung der Artenmischung, die Förderung der natürlichen Verjüngung sowie die Erhaltung und angemessene räumliche Verteilung des Totholzes in der Landschaft berücksichtigt.

1 Introduction

Understanding the dynamics and developmental stages of forest ecosystems is essential for promoting sustainable forestry and formulating effective management strategies (Oikonomakis & Ganatsas, 2012). In this context, the conservation of forests and their biological diversity remains a central long-term objective of forest management. The preservation of deadwood is particularly crucial due to its ecological importance (Banaś *et al.*, 2014; Sefidi & Etemad, 2015). Deadwood contributes significantly to nutrient cycling, forest regeneration, productivity, ecosystem sustainability, and the maintenance of biodiversity within forest environments (Angers *et al.*, 2005; Radu *et al.*, 2006; Aticie *et al.*, 2008; Sefidi *et al.*, 2015; Habashi *et al.*, 2017; De Meo *et al.*, 2019; Lo Monaco *et al.*, 2020). As stated in the 2nd and 3rd Ministerial Conferences for the Protection of Forests in Europe (MCPFE), deadwood plays an essential role within the forest as it serves as a habitat for many species of invertebrates, fungi, bryophytes, lichens, amphibians, small mammals, and birds (Rahman *et al.*, 2008; Sefidi & Etemad, 2015). Previous studies have observed the positive effect of deadwood as a source of carbon storage, which included 3-12% and 10-20% of the above-ground biomass in disturbed as well as virgin forests, respectively (Brown, 2002; De Meo *et al.*, 2019).

Despite the many ecological benefits of deadwood, several potential drawbacks have also been noted, including an increased risk of forest fires, a higher likelihood of disease outbreaks and biotic disturbances, and a possible decline in the aesthetic value of the forest (Radu, 2006). However, forest managers should emphasize the ecological role of deadwood in supporting forest biodiversity by actively promoting public awareness and education (Pastorella *et al.*, 2016; Simkin *et al.*, 2020; Kiadaliri *et al.*, 2023). In many regions, deadwood conservation remains limited, often due to inadequate management practices in both commercial forests and even within protected areas (Puletti *et al.*, 2019). To sustain forest structure and enhance the ecological functions of deadwood, it is essential to assess various characteristics, including deadwood type (snag, log, stump), abundance, volume, decomposition rate, and decay class (Bayraktar *et al.*, 2020).

The quantitative and qualitative characteristics of deadwood in forest ecosystems are influenced by natural factors (stand age and type, amount of growth, development stages of stands, natural disturbances patterns, such as type, frequency, severity, distribution, *etc.*) and human interference (forest management goals, road network and harvesting operations) (Behjou *et al.*, 2018; Kiadaliri *et al.*, 2023).

Numerous studies worldwide have shown that the number and volume of deadwood in managed forests are typically lower than in intact forests, primarily due to harvesting operations and specific management objectives (Green & Peterken, 1997; Paletto *et al.*, 2014). Additionally, research (Banaś *et al.*, 2014; Herrero *et al.*, 2016; Topacoğlu *et al.*, 2017) suggests that older forests generally exhibit higher numbers and volumes of deadwood compared to younger forests. In old forests, deadwood is distributed across all decay classes, whereas in young forests, deadwood is primarily confined to the first decay class.

The formation of deadwood in forests, whether arising from biological disturbances during forest stand development or from natural and human-induced disturbances, exhibits varying degrees of decay severity (Zolfeghari, 2005). Some studies categorize the decay of deadwood into four distinct classes (Motta *et al.*, 2006), while others have proposed a five-class system to describe the severity of decay (Miura & Yamamoto, 2003; Oaten & Larsen, 2008).

Deadwood in forests exists in various forms, which have been classified in multiple studies (Sefidi & Etemad, 2015; Habashi *et al.*, 2017). However, most studies categorize deadwood into two primary groups: snags and logs (Oaten & Larsen, 2008). Logs include fallen trees, large branches, and remnants from harvesting operations or natural disturbances. According to Berg (1994), 26% of species on the Swedish Red List, including endangered and vulnerable species, are associated with logs. Furthermore, logs and stumps play a protective role for regeneration in cold temperate northern and semi-mountainous forests (Hofgaard, 1993; Takahashi, 2000).

The continuity and dynamics of a forest are closely linked to the successful regeneration of forest trees. Consequently, the establishment and persistence of regeneration in natural forests depend on the formation of canopy gaps, which can be created by deadwood in forest stands (Delfan Abazari *et al.*, 2004) or by disturbances, whether natural or human-induced.

One of the key ecological functions of deadwood is its influence on forest light conditions. Zolfeghari *et al.* (2007), in their study on the role of deadwood in natural regeneration in the Hyrcanian forests of northern Iran, found that seedling abundance was highest near highly decayed deadwood. They also reported a significant correlation between canopy gap size and the density of regenerated seedlings. Regeneration density, however, is influenced by several additional factors, including light availability, the presence of mature seed-bearing trees, and tree species composition.

Increased levels of light, combined with greater availability of nutrients and moisture, can also promote the growth of competing grassland vegetation, which may hinder tree regeneration (Kuluvainen & Juntunen, 1998). Furthermore, higher nutrient levels in the soil can enhance seedling growth rates (Sohrabi *et al.*, 2019). In a study of conifer stands in Taiwan, Liao *et al.* (2003) found that deadwood significantly shaped natural regeneration patterns, with logs providing protective microhabitats that support the establishment of seedlings.

Understanding the frequency and characteristics of deadwood is essential for forest managers to sustain ecosystem productivity and ecological processes. This knowledge can also inform the development of quantitative guidelines for the effective management of deadwood in forest stands. Although some studies have addressed the ecological significance of deadwood in the lowland forests of northern Iran (Tavankar *et al.*, 2014; Kiadaliri *et al.*, 2023), there remains a lack of research specifically examining the quantitative and qualitative attributes of deadwood and the abundance of natural regeneration across different growth stages in protected forest areas within this ecosystem. The findings of this study are expected to provide novel and valuable insights for biodiversity conservation and the sustainable management of protected lowland forests.

The objectives of this study are to address the following research questions within the study area:

1. What is the abundance and quality (decay class) of different deadwood types (snags, logs, and stumps)?
2. Which tree species and growth stage are most frequent in the natural regeneration?

2 Materials and Methods

2.1 Study area

This research was conducted in a protected area of Noor Forest Park, located in Mazandaran Province, northern Iran. The park represents one of the last remaining fragments of lowland plain forests within the Hyrcanian region. Since its establishment five decades ago, the forest has been free from forestry operations and has been managed exclusively for conservation purposes as a forest reserve. A 25-hectare section of this forest, situated between latitudes 36°36′ and 36°32′ N and longitudes 52°08′ and 52°02′ E, at an elevation of 28 meters above sea level, has recently been designated as an educational and research site under the management of the Faculty of Natural Resources at Tarbiat Modares University.

The study site is located approximately 3 kilometers from the city of Noor and about 200 meters from the Caspian Sea. A stream along the eastern boundary of the forest contributes to periodic flooding during certain spring months in some years. The region receives an average annual precipitation ranging from 900 to 1,000 mm, with a mean annual temperature of 16.1 °C. Autumn is the wettest season, accounting for approximately 30% of the total annual rainfall, while August is typically the driest month. The lowest daily temperatures are recorded in January, whereas the highest occur in August. Frost events are occasionally observed in January and February (Varamesh & Tabari, 2000).

Geologically, the forest belongs to the Quaternary period and, in terms of facies, is classified as part of the alluvial plains. The bedrock consists primarily of calcareous-origin sediments. The soil texture is predominantly clay loam, with surface soils exhibiting a weakly acidic pH that becomes increasingly alkaline with depth (Barzehkar, 1995).

The forest supports a diverse range of tree species, including alder (*Alnus subcordata* C.A.M.), maple (*Acer velutinum* Boiss.), hornbeam (*Carpinus betulus* L.), oak (*Quercus castanifolia* C.A.M.), and ironwood (*Parrotia persica* C.A.M.). Notably, the presence of native and endemic species such as the Caucasian elm (*Ulmus minor* Miller) and Persian poplar (*Populus caspica* Bornm.) underscores the ecological significance of this forest. The herbaceous layer is dominated by *Carex sylvatica*, which comprises over 50% of the ground vegetation cover. The location of the study area is illustrated in Figure 1.

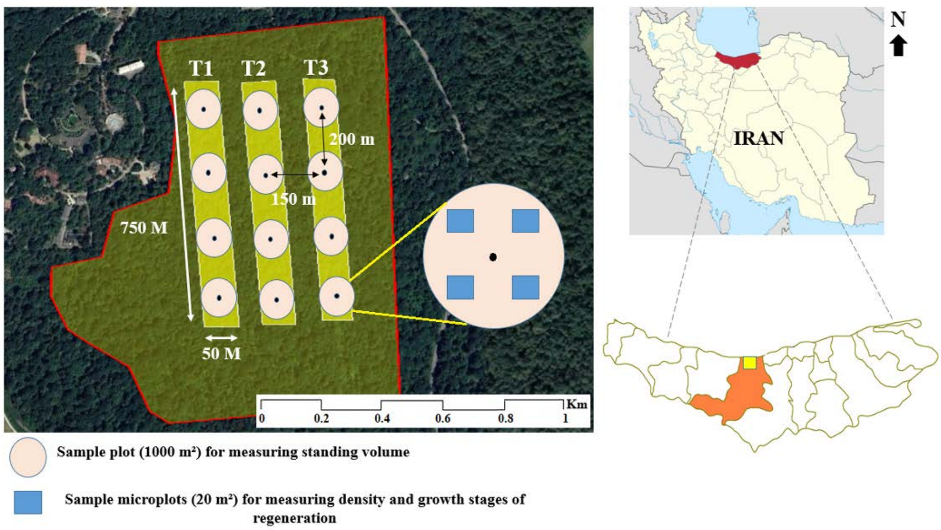

Figure 1: Geographical location of the studied area (protected Forest of Noor city, North of Iran). See text for details on sample design.

Abbildung 1: Geografische Lage des untersuchten Gebietes (geschützter Wald der Stadt Noor im Norden Irans). Für Details zum Stichprobendesign wird auf den Text verwiesen.

2.2 Experimental design

To assess the quantitative and qualitative characteristics of deadwood, three transects were established, each measuring 50 meters in width and 750 meters in length. Within these transects, all deadwood components were recorded, including snags (defined as standing dead trees with a diameter at breast height [d.b.h.] > 7.5 cm and a height > 1.30 m), logs (fallen deadwood with a diameter at half-length > 7.5 cm and a length > 1 m), and stumps (deadwood with a top diameter > 7.5 cm and a height < 1.30 m), following the classification criteria of Keren and Diaci (2018). Representative images of the different deadwood types—snags, logs, and stumps—are presented in Figure 2.

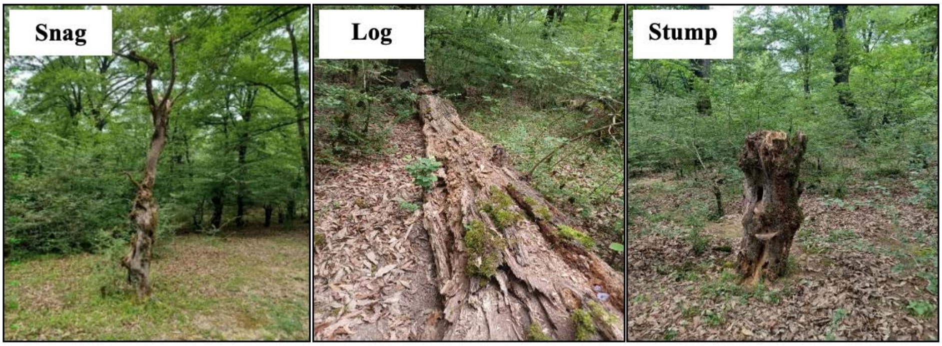

Figure 2: Deadwood types (snag, log and stump) in the protected lowland forest of Noor city, North of Iran.

Abbildung 2: Totholzarten (stehendes Totholz, liegender Baumstamm und Stumpf) im geschützten Tieflandwald der Stadt Noor im Norden Irans.

The volume of logs and stumps was calculated using Huber's formula according to equation (1) and the volume of snags was calculated based on equation 2 (Harmon & Sexton, 1996).

$$V = g_m \times h \qquad (1)$$

where V is the volume (m^3), g_m is the mid-point cross-sectional area (m^2), and h is the length (m).

$$V = g_m \times h \times f \qquad (2)$$

where V is the volume (m^3), g_m is basal area at 1.30 m height (m^2), *f* is the shape coefficient (=0.5), and h is the height (m).

Classification of the severity or decay class (DC) of deadwood was done according to the method of Moghimian *et al.* (2014) shown in Table 1.

Table 1: Decay class (DC) of deadwood and their characteristics.

Tabelle 1: Zerfallsklasse (DC) von Totholz und deren Beschreibung.

Decay class 1	Less than 5 years have passed since the tree died. The bark and appearance of the tree have not changed much.
Decay class 2	The tree has started to decompose, the color of the wood has turned brown and white spots can be seen, but wood is still hard and its physical and chemical properties have not changed much (5-10 years since the tree died).
Decay class 3	The decay is advancing and the physical and chemical wood properties have changed. The wood shows cracks, darkens in color and loses its original shape (10-15 years since the tree died).
Decay class 4	The wood is completely rotten, deformed and easily crumbles on impact (more than 15 years since the tree died).

To assess the standing volume within the forest, a systematic sampling approach was employed using 12 circular sample plots, each with an area of 1,000 m^2 (radius 17.84 m), arranged within 150 m × 200 m grid cells. The placement of plots followed a systematic design initiated from a randomly selected starting point (Figure 1). Within each sample plot, data were collected on tree species, diameter at breast height (d.b.h.) for trees with a d.b.h. greater than 5 cm, total tree height, basal area, and standing volume. Additionally, four micro-plots measuring 4 m × 5 m were established within each circular plot (Figure 1) to assess natural regeneration. In these micro-plots, regenerating species were recorded separately according to species type and developmental stage, categorized as seedling (height < 50 cm), sapling (height 50–200 cm), and thicket (height 200–600 cm), in accordance with the classification system proposed by Marvi Mohajer (2011).

2.3 Data Analysis

To analyze the data, assumptions of normality and homogeneity of variances were assessed using the Kolmogorov-Smirnov test and Levene's test, respectively. For normally distributed data with homogeneous variances, one-way analysis of variance (ANOVA) was employed to evaluate differences in the percentage of total species regeneration. In cases where the data did not meet these assumptions, the non-parametric Kruskal-Wallis test was applied. Additionally, Duncan's multiple range test was used for post-hoc comparisons of means. All statistical analyses were performed using SPSS software, version 21.

3 Results

3.1 Quantitative characteristics of standing living trees

The total number, volume, and basal area of living trees in the studied forest were estimated at 312.5 stems per hectare, 200.55 m^3, and 25.87 m^2, respectively (Table 2). Among the recorded species, ironwood (*Parrotia persica* C.A.M.) exhibited the highest values in terms of stem count, standing volume, and basal area. Hornbeam (*Carpinus betulus* L.) ranked second in stem count following wych elm (*Ulmus glabra* Hudson), but in terms of volume and basal area, it was the most dominant species after ironwood. In contrast, other tree species—such as Alnus subcordata C.A.M. (*Caucasian alder*), *Ficus carica* L. (fig), *Tilia platyphyllos* Scop. (large-leaved lime), *Acer velutinum* Boiss. (Persian maple), *Quercus castaneifolia* C.A.M. (chestnut-leaved oak), and *Populus caspica* Bornm. (Caspian poplar)—were represented by the lowest values in terms of number, volume, and basal area (Table 2).

Table 2: Structural characteristics of living trees (mean diameter at breast height, mean height, number, volume and basal area of species).

Tabelle 2: Strukturmerkmale lebender Bäume (Brusthöhendurchmesser, Höhe, Anzahl, Volumen und Grundfläche der Arten).

Species	d.b.h. (cm)	Heigh t (m)	Number (ha^{-1})	Share number (%)	Volume (m^3 ha^{-1})	Share volume (%)	Basal area (m^2 ha^{-1})	Share basal area (%)
Parrotia persica C.A.M.	29.6	12.6	149.17	47.70	64.18	32.00	10.29	39.79
Carpinus betulus L.	37.5	7.64	60.83	19.50	51.61	25.73	6.70	25.90
Alnus subcordata C.A.M.	45.8	18.8	1.67	5.00	2.48	1.23	0.27	1.03
Ficus carica L.	25.0	13.1	8.33	2.70	2.63	1.31	0.41	1.58
Tilia platyphyllos Scop.	39.1	19.1	3.33	1.10	3.70	1.85	0.40	1.55
Ulmus glabra Huds.	29.9	17.7	80	25.60	49.43	24.65	5.63	21.78
Acer velutinum Boiss.	14.3	13.25	2.5	0.80	0.39	0.20	0.04	0.16
Quercus castaneifolia C.A.M.	24.7	18.8	2.5	0.80	1.13	0.56	0.12	0.45
Populus caspica Bornm.	78.4	25	4.17	1.30	25.01	12.47	2.01	7.76
Total			312.5	100	200.55	100	25.87	100

Notably, no individuals of boxwood (*Buxus hyrcana* Pojark.) or date-plum (*Diospyros lotus* L.) with a diameter at breast height (d.b.h.) greater than 5 cm were observed in the sample plots. The highest tree density per hectare was recorded in the 25 cm diameter class (62 stems), while the lowest density was observed in the 95–100 cm diameter class (2 stems) (Figure 3). Across all species, stem density was greatest in the intermediate diameter classes (20–40 cm), indicating a predominance of mid-sized trees within the forest structure (Figure 3).

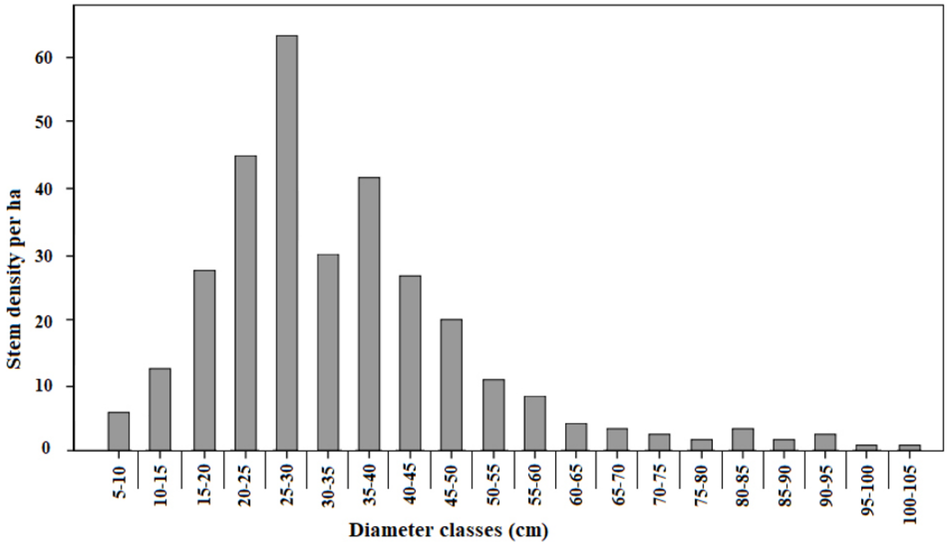

Figure 3: Stem density of all living tree species (per hectare) in diameter classes.

Abbildung 3: Stammzahl aller lebenden Baumarten (pro Hektar) in Durchmesserklassen.

3.2 Quantitative and qualitative characteristics of deadwood

The number and volume of deadwood were estimated at 35.29 elements per hectare and 9.77 m^3 ha^{-1}, respectively (Table 3). With regards to species, hornbeam (*Carpinus betulus* L.) accounted for the highest proportion of deadwood, representing 39.8% of the total number and 35.92% of the total volume. In contrast, date-plum (*Diospyros lotus* L.) exhibited the lowest number of deadwood individuals, while boxwood (*Buxus hyrcana* Pojark.) had the lowest deadwood volume.

When examining the ratio of deadwood volume to the volume of living standing trees, oak (*Quercus castaneifolia* C.A.M.) showed the highest relative deadwood volume, exceeding the volume of its living counterparts with a ratio of 109.71%. Overall, the volume of total deadwood represented 4.88% of the total volume of living standing trees across the study area (Table 3).

Table 3: The number and volume of total deadwood elements. NDW: number of deadwood elements; VDW: volume of deadwood elements; VT: volume of standing (living) trees.

Tabelle 3: Anzahl und Volumen des gesamten Totholzes. NDW: Anzahl des Totholzes; VDW: Volumen des Totholzes; VT: Volumen der stehenden (lebenden) Bäume.

Deadwood species	NDW (ha^{-1})	VDW ($m^3 ha^{-1}$)	VT ($m^3 ha^{-1}$)	VDW/VT (%)
Parrotia persica C.A.M.	7.82	1.65	64.18	2.56
Carpinus betulus L.	14.04	3.51	51.61	6.80
Alnus subcordata C.A.M.	1.60	0.20	2.48	8.06
Ficus carica L.	3.02	0.29	2.63	11.07
Tilia platyphyllos Scop.	0.27	0.10	3.70	2.73
Ulmus glabra Huds.	5.16	1.98	49.43	4.00
Buxus hyrcana Pojark.	0.62	0.01	25.01	3.07
Diospyrus lotus L.	0.18	0.04	0.00	0.00
Quercus castaneifolia C.A.M.	1.87	1.24	1.13	109.71
Populus caspica Bornm.	0.71	0.77	0.00	0.00
Total	35.29	9.77	200.55	4.88

Overall, the highest number and volume of deadwood were observed in the diameter classes <20 cm and 20–40 cm, respectively (Table 4). Among snags, the 20–40 cm diameter class exhibited the greatest stem density (2.49 individuals per hectare), whereas the highest volume (0.97 m^3/ha) was recorded in the >80 cm diameter class. For logs and stumps, the highest number of individuals occurred in the <20 cm diameter class, with 14.4 and 1.6 individuals per hectare, respectively. However, the maximum volume of logs (2.89 m^3/ha) and stumps (0.05 m^3/ha) was found in the 40–60 cm diameter class (Table 4).

Table 4: Number and volume of deadwood per hectare by diameter class and deadwood type.

Tabelle 4: Anzahl und Volumen von Totholz pro Hektar in Durchmesserklassen und Totholzart.

Diameter classes (cm)	Snag		Log		Stump		All	
	Number (ha^{-1})	Volume (m^3 ha^{-1})	Number (ha^{-1})	Volume (m^3 ha^{-1})	Number (ha^{-1})	Volume (m^3 ha^{-1})	Number (ha^{-1})	Volume (m^3 ha^{-1})
< 20	1.51	0.05	14.4	0.57	1.60	0.01	17.51	0.63
20-40	2.49	0.56	9.51	2.48	1.42	0.03	13.42	2.07
40-60	1.33	0.76	1.33	2.89	0.80	0.05	3.46	4.70
60-80	0.27	0.53	0.36	0.86	0.09	0.01	0.72	1.40
>80	0.18	0.97	0.00	0.00	0.00	0.00	0.18	0.97
Total	5.78	2.87	25.6	6.80	3.91	0.10	35.29	9.77

According to the results, the total number of snags, logs, and stumps was 5.8, 25.6, and 3.91 individuals per hectare, respectively (Table 5). The corresponding volumes per hectare were 2.869 m^3 for snags, 6.8024 m^3 for logs, and 0.0997 m^3 for stumps. The highest volume of logs (2.55 m^3/ha) and stumps (0.048 m^3/ha) was associated with *Carpinus betulus*, whereas the highest snag volume (1.08 m^3/ha) was recorded for *Ulmus glabra*.

No snags were recorded for *Ulmus glabra*, *Populus caspica*, *Quercus castaneifolia*, or *Diospyros lotus*, and no stumps were observed for *Tilia platyphyllos*, *Diospyros lotus*, or *Populus caspica*. Notably, the volume of logs from *Carpinus betulus* accounted for 26.05% of the total deadwood volume within the studied forest (Table 5).

Table 5: Number and volume of deadwood per hectare by deadwood type and tree species.

Tabelle 5: Anzahl und Volumen von Totholz pro Hektar nach Totholzart und Baumart.

Species	Snag (ha^{-1})	Log (ha^{-1})	Stump (ha^{-1})	Snag (m^3 ha^{-1})	Log (m^3 ha^{-1})	Stump (m^3 ha^{-1})	All deadwood volume (m^3 ha^{-1})
Parrotia persica C.A.M.	0.82	6.49	1.24	0.0678	1.5621	0.0161	1.65
Carpinus betulus L.	2.49	9.51	1.33	0.9118	2.5498	0.048	3.51
Alnus subcordata C.A.M.	0.27	1.07	0.27	0.0551	0.1272	0.0176	0.20
Ficus carica L.	0.62	2.22	0.18	0.0433	0.2473	0.0006	0.29
Tilia platyphyllos Scop.	0.00	0.27	0.00	0.0000	0.1010	0.0000	0.10
Ulmus glabra Huds.	1.24	3.29	0.62	1.0848	0.8781	0.0133	1.98
Buxus hyrcana Pojark.	0.27	0.18	0.18	0.0021	0.0022	0.0003	0.00
Diospyrus lotus L.	0.00	0.18	0.00	0.0000	0.0354	0.0000	0.03
Quercus castaneifolia C.A.M.	0.00	1.78	0.09	0.0000	1.2359	0.0038	1.24
Populus caspica Bornm.	0.09	0.62	0.00	0.7041	0.0634	0.0000	0.77
Total	5.80	25.60	3.91	2.869	6.8024	0.0997	9.77

According to species type and decay stage, the highest number of deadwood trees in most species, including *Parrotia persica* C.A.M., *Ficus carica* L., *Ulmus glabra* Hudson, *Diospyrus lotus* L., *Quercus castaneifolia* C.A.M., and *Populus caspica* Bornm., were found in decay class (DC) 2 and 3 (Table 6). In contrast, *Carpinus betulus* and *Alnus subcordata* exhibited the highest number of deadwood trees in decay class 4. Overall, it can be concluded that most deadwood in the studied forest were classified into decay classes 2, 3, and 4 (Table 6).

Regarding decay class distribution, *Ulmus glabra* had the highest percentage of deadwood volume per hectare in decay classes 1 and 2, whereas *Carpinus betulus* exhibited the highest percentage of deadwood volume per hectare in decay classes 3 and 4 (Figure 4).

Table 6: Number and volume per hectare of total deadwood according to species and decay class (DC).

Tabelle 6: Anzahl und Volumen pro Hektar Gesamttotholz nach Art und Zerfallsklasse (DC).

	Number (per ha)				Volume (m^3 ha^{-1})			
Species	DC1	DC2	DC3	DC4	DC1	DC2	DC3	DC4
Parrotia persica C.A.M.	0.8	1.78	3.11	2.84	0.3515	0.3446	0.5565	0.3922
Carpinus betulus L.	0.00	2.49	4.53	6.31	0.0000	0.7445	1.7374	1.0275
Alnus subcordata C.A.M.	0.09	0.44	0.36	0.71	0.0093	0.0604	0.0604	0.0627
Ficus carica L.	0.09	1.96	0.80	0.18	0.0045	0.1976	0.0674	0.0210
Tilia platyphyllos Scop.	0.09	0.09	0.00	0.09	0.0214	0.0752	0.0000	0.0042
Ulmus glabra Huds.	0.8	2.49	0.98	0.89	0.7934	0.8295	0.2329	0.1200
Buxus hyrcana Pojark.	0.27	0.36	0.00	0.00	0.0009	0.0037	0.0000	0.0000
Diospyrus lotus L.	0.00	0.00	0.18	0.00	0.0000	0.0000	0.0354	0.0000
Quercus castaneifolia C.A.M.	0.09	0.44	0.62	0.44	0.0035	0.0757	1.0924	0.0678
Populus caspica Bornm.	0.00	0.27	0.36	0.09	0.0000	0.7283	0.0298	0.0240
Total	2.22	10.31	10.93	11.56	1.1845	3.0662	3.8122	1.7194

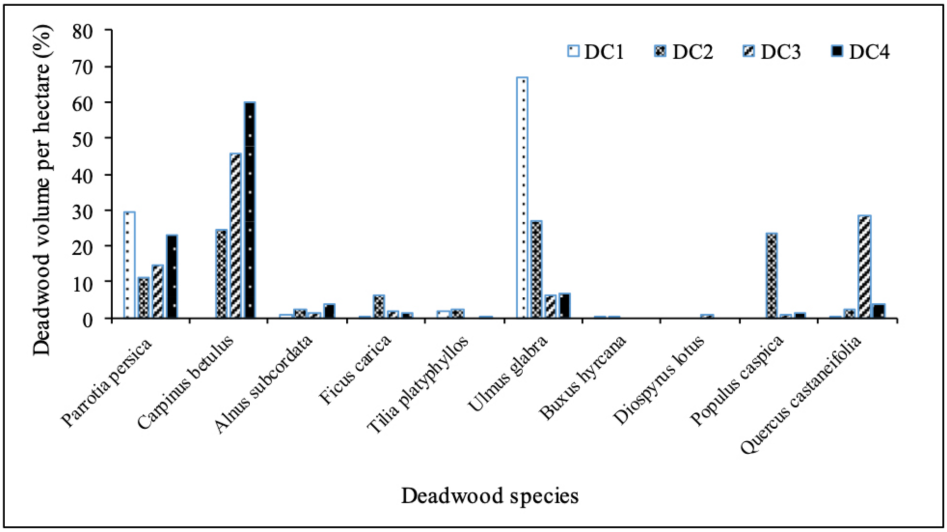

Figure 4: Proportion of deadwood volume (per hectare) by species and decay class (DC).

Abbildung 4: Anteil des Totholzvolumens (pro Hektar) nach Totholzart und Zerfallsklasse (DC).

3.3 Natural regeneration in the forest

The results of species regeneration (Figure 5) indicated that *Parrotia persica* exhibited the highest regeneration frequency among the 11 species, with no significant difference observed compared to *Carpinus betulus*. Conversely, *Prunus divaricata* showed the lowest regeneration frequency, which was not significantly different from *Danae racemosa*, *Populus caspica*, *Pterocarya fraxinifolia*, and *Ficus carica*.

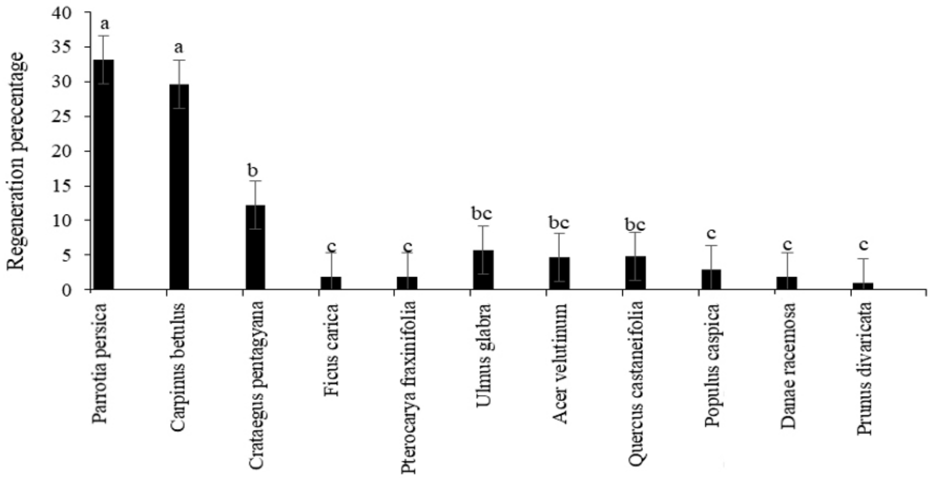

Figure 5: The percentage of total natural regeneration of the species.

Abbildung 5: Anteil der Baumarten an der Naturverjüngung.

In most species, the highest percentage of regeneration was observed in the seedling and sapling stages. For example, in *Parrotia persica*, more than 25% of the total regeneration occurred in the seedling stage, over 5% in the sapling stage, and approximately 1% in the thicket stage (Figure 6).

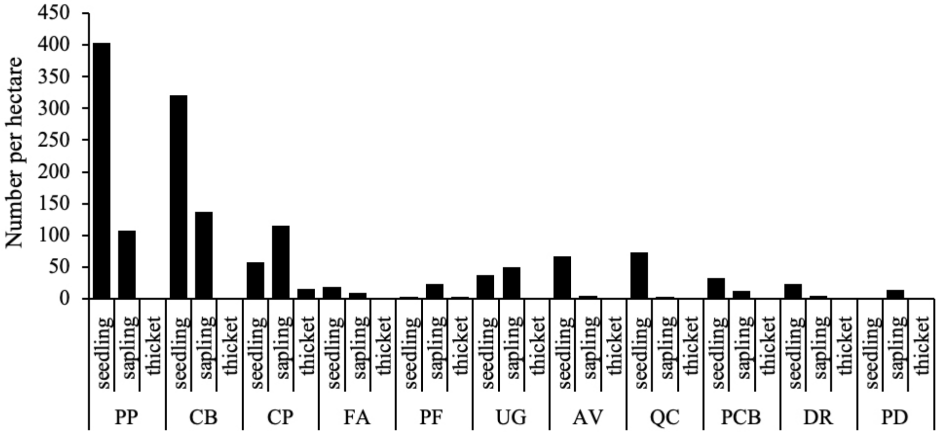

Figure 6: Frequency of natural regeneration per hectare according to species and vegetative stages. Used abbreviations in the figure are PP (Parrotia persica C.A.M.), CB (Carpinus betulus L.), CP (Crataegus pentagyna Waldst. & Kit. ex Willd.), FA (Ficus carica L.), PF (Pterocarya fraxinifolia (lam) Spach.), UG (Ulmus glabra Hudson), AC (Acer velutinum Boiss), QC (Quercus castaneifolia C.A.M.), PCB (Populus caspica Bornm.), DR (Daneae racemosa L.), and PD (Prunus divaricata Ledeb).

Abbildung 5: Häufigkeit der natürlichen Verjüngung pro Hektar nach Arten und Vegetationsstadien. Verwendete Abkürzungen sind PP (*Parrotia persica* C.A.M.), CB (*Carpinus betulus* L.), CP (*Crataegus pentagyna* Waldst. & Kit. ex Willd.), FA (*Ficus carica* L.), PF (*Pterocarya fraxinifolia* (lam) Spach.), UG (*Ulmus glabra* Hudson), AC (*Acer velutinum* Boiss), QC (*Quercus castaneifolia* C.A.M.), PCB (*Populus caspica* Bornm.), DR (*Daneae racemosa* L.) und PD (*Prunus divaricata* Ledeb).

4 Discussion

4.1 Quantitative and qualitative characteristics of deadwood

The results of the present study revealed that the abundance and volume of deadwood were 35.29 individuals per hectare and 9.77 m^3 per hectare, respectively. In comparison, a similar study conducted in a lowland forest in northern Iran (Sisangan Forest Park) reported a higher density and volume of deadwood, with 50 stems per hectare and 102.5 m^3 per hectare, respectively (Kiadaliri *et al.*, 2023). Additionally, Tavankar *et al.* (2014) observed significantly lower snag density and volume in selectively logged and accessible stands in another lowland forest. Consistent with our findings, a study conducted in Kheyrud Nowshahr forests in Mazandaran province found that in protected (low-intervention) stands, the volume of deadwood was 0.9 m^3 per hectare greater that than in managed (high-intervention) stands (Sefidi & Marvi Mohadjer, 2010).

Research conducted in Europe has also demonstrated that, depending on the management practices employed, the average volume of deadwood in managed beech forests typically does not exceed 10 m^3 per hectare (Meyer, 1999; Tabaku, 2000). Similarly, in North American forests, the volume of snag deadwood in intervened forests (4 m^3 per hectare) was significantly lower than that in protected forests (26.5 m^3 per hectare) (McComb & Noble, 1980). Previous studies in northern Iran have revealed varying deadwood volumes across forests with different characteristics. Such discrepancies are likely attributable to differences in forest structure, tree age, environmental factors, and the prevalence of pests and diseases

In this forest, a total of 10 species of deadwood were identified. *Carpinus betulus* accounted for the largest proportion of deadwood, representing 19.5% of the total number and 25.73% of the total volume. The highest abundance of deadwood was associated with *Carpinus betulus*, while other species were less represented. This pattern may be attributed to the ecological characteristics of *Carpinus betulus*, coupled with its relatively low longevity compared to other species such as *Parrotia persica* and *Quercus castaneifolia*, which tend to persist longer before succumbing to decay (Moridi *et al.*, 2016)

Consistent with other studies conducted in lowland forests (Kiadaliri *et al.*, 2023), our investigation found that log deadwood was the most abundant type, surpassing both snags and stumps. It is generally accepted that in conservation forests, where harvesting is absent, the proportion of stumps is lower, while the proportion of logs is higher. This higher log volume can be attributed to the natural fall of small trees, often due to competition or other ecological disturbances (Behjou *et al.*, 2018; Lo Monaco *et al.*, 2020). A study on unmanaged beech forests in northern Iran reported that logs accounted for 78% of the total deadwood volume, while snags comprised 22%. Similarly, in a mixed beech-hornbeam stand, snag and log deadwoods accounted for 64% and 36% of the total deadwood volume, respectively (Sefidi *et al.*, 2009). These findings align closely with the results of the present study.

In our research, the number of snags, at 5.8 stems per hectare, was relatively low compared to other studies. This observation is consistent with previous reports indicating an increase in snag density in managed forests relative to protected forests (Amoozad *et al.*, 2018; Sefidi *et al.*, 2009). Additionally, we found that the volume of log deadwood was the highest at 6.8 m^3/ha. These results contrast with those of Reid *et al.* (1996), who reported that in protected forest stands, the volume of log deadwood was lower than that of snag deadwood (12 m^3/ha versus 42 m^3/ha).

In our study, deadwood in decay class 4 exhibited the highest abundance, with 11.6 stems per hectare, while deadwood in decay class 3 represented the highest volume, with 3.8 m^3 per hectare. Conversely, the abundance and volume of trees in decay class 1 were the lowest. This pattern may be attributed to environmental factors within the forest stand, such as tree age and the accelerated decomposition rates of certain tree species, which likely contribute to the increased number and volume of deadwood in the higher decay classes.

Regarding decay type, the highest abundance of deadwood was found in decay classes 3 and 4, which aligns with the findings of Kooch *et al.* (2010), but contrasts with research conducted in natural European beech forests (Alidadi *et al.*, 2014). Unlike the forests of northern Iran, which are characterized by a humid temperate climate, European forests are situated in cold, dry conditions. These environmental differences contribute to a slower decomposition process in European forests (Angers *et al.*, 2005). Consequently, due to the warmer climate in northern Iran, deadwood decomposes more rapidly (Safidi *et al.*, 2013). This suggests that decay rates in the Hyrcanian forests are faster than that in European forests.

Sefidi and Marvi Mohajer (2010) found that 72% of deadwood in northern Iran's forests was classified in decay classes 3 and 4, indicating that these stands are in an advanced stage of ecological dynamics. This higher proportion of advanced decay may be linked to historical forest management practices, including extensive tree harvesting and logging, which allowed a greater amount of light to reach the forest floor and provided sufficient time for fallen and damaged trees to decay. The observed predominance of deadwood in decay classes 3 and 4, along with the minimal presence of deadwood in earlier decay stages, supports this interpretation.

4.2 Natural regeneration in the forest

In our study, the total regeneration density was 1539.5 stems per hectare, with the highest regeneration observed in the seedling growth stage, comprising 1038.3 stems per hectare. The relatively low regeneration in certain areas may be attributed to the presence of blackberry (*Rubus* spp.) both in forest gaps and within the understory, as well as to incomplete drainage in some scattered regions of the forest.

The establishment of natural regeneration is generally influenced by site characteristics, stand composition, management history, and the role of deadwood within forest stands. Several studies, including the findings of Kooch *et al.* (2010), have indicated that the highest regeneration density is typically associated with log deadwood in decay class 4, while the lowest density is found in snag deadwood in decay class 1. Habashi (1997) reported a positive relationship between deadwood and the regeneration frequency of *Ulmus glabra* in the forests of the Vaz region. Additionally, Mohammadnejad Kiasri and Rahmani (2001) found that in a mixed beech-hornbeam forest in northern Iran, the abundance of *Fagus sylvatica* seedlings was higher in areas surrounding deadwood compared to those near living standing trees.

In our study, *Parrotia persica* and *Carpinus betulus* exhibited the highest regeneration densities, with greater frequencies observed at the seedling stage compared to the sapling and thicket stages. This trend suggests that competition among regenerated individuals, coupled with limited light availability in the understory, leads to a gradual decline in the number of saplings and thickets. Both species demonstrate a high abundance in the tree stratum, which underscores their notable adaptability to the climatic conditions of the Hyrcanian forests in northern Iran. Furthermore, the presence of their deadwood, particularly at advanced stages of decay, likely plays a significant role in supporting the ecological integrity and long-term sustainability of the forest ecosystem.

The findings of the current study suggest that the abundance of log deadwood in advanced stages of decay (classes 3 and 4) promotes significant regeneration. Deadwood in the final stages of decay, through the process of complete decomposition, facilitates the return of nutrients to the forest soil, thereby enhancing soil fertility. As a result, areas with decomposed deadwood and their surrounding environments create favorable conditions for the establishment and growth of natural regeneration. Similarly, a study conducted in Italy by Motta *et al.* (2006) found that the highest rate of *Picea abies* seedling establishment occurred around deadwood in advanced to complete decay (decay classes 3 and 4), which aligns with the results observed in our study. Furthermore, Hang Chang *et al.* (2001) in *Chamaecyparis* forests in northern Taiwan concluded that the removal of deadwood from the forest floor had a detrimental impact on sapling frequency.

For effective forest management, it is recommended that both snag and log deadwood be retained within the forest ecosystem. Motta *et al.* (2006), in their study on forest structure, regeneration density, and its relationship with deadwood in Italy, demonstrated that deadwood in advanced stages of decay provides more favorable conditions for regeneration establishment than newly fallen trees. The removal of deadwood can, therefore, limit future natural regeneration, particularly in nutrient-poor soils. Given the critical role of deadwood in supporting forest regeneration, Svobota *et al.* (2010) argue that the potential benefits of removing dead and dying trees from semi-natural forests must be carefully balanced against the possible negative impacts on natural regeneration and forest biodiversity, especially in spruce-dominated forests.

While the aforementioned observations have primarily been reported in montane forest ecosystems, similar functions can also be anticipated in lowland forest environments. Overall, the findings of the present study suggest that the abundance, type, and degree of decay or decomposition of deadwood play a significant role in the establishment of natural regeneration, as well as in the structure and composition of the forest stand.

5 Conclusion

In this study, the total volume of deadwood was 9.77 m^3/ha, with *Carpinus betulus* accounting for the largest proportion of both the number and volume of deadwood. The results also indicated that log deadwood had both a higher volume and a greater number compared to snags and stumps. Regarding decay stages, the majority of deadwood abundance was observed in decay classes 4 and 3, while the least was found in decay class 1. *Parrotia persica* exhibited the highest regeneration frequency, with no significant difference from *Carpinus betulus*. Natural regeneration of these species was predominantly concentrated in the seedling stage, with fewer individuals in the sapling and thicket stages.

In general, the abundance of deadwood, the species composition of trees and shrubs, and the degree of decay significantly influence the formation of forest structure and the establishment of natural regeneration. It is recommended that management strategies for protected forests prioritize the enhancement of stand volume, regulation of species admixture, the promotion and expansion of natural regeneration, and the proper maintenance of deadwood within the forest ecosystem. Furthermore, the management of deadwood in these forests should focus on biodiversity conservation, which can contribute to mitigating the effects of global warming.

Authors' contributions

Esmaeil Ahmadi and Masoud Tabari conceived and designed the experiments. Material preparation and data collection were performed by Esmaeil Ahmadi and Masoud Tabari. Esmaeil Ahmadi and Hadi Sohrabi performed the experiments and analyzed the data. All authors wrote, read and approved the final manuscript. Rachele Venanzi was responsible for final editing.

Declarations

Competing interests. The authors declare no competing interests.

Conflict of interest

The authors declare that they have no conflict of interest.

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