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The impact of forest degradation on the structural heterogeneity of natural broadleaved forests in Arasbaran region of Iran

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Abstract: A variety of diversity indices and structural measurements have been defined to evaluate and analyze forest structure. These measures represent mathematical constructions of species, dimensional, and location diversity.
The present study aimed to quantify and compare the current spatial structure of two groups of natural stands, with different levels of degradation, i.e., more degraded and less degraded stands, in the Arasbaran forests of Iran.
Data were collected from 177 permanent sample plots from six forest stands in the Arasbaran forests of northwestern Iran. Spatial structure was quantified using neighborhood-based structural indices related to species mingling, size differentiation, and spatial distribution. The complex structural diversity index (SI) and the forest structure types of the stands were investigated simultaneously to compare the two different groups.
Results showed that forest degradation significantly reduced structural heterogeneity. In less degraded stands, structural diversity indices including species mingling (M = 0.36), diameter at breast height differentiation (TD = 0.27), tree height differentiation (TH = 0.20) and distance to neighbors (D = 1.8) had consistently higher values compared to more degraded areas, although the spatial distribution of trees showed a clumped pattern in both groups. In addition, the higher SI value (0.394) indicated a medium level of structural diversity in less degraded stands, compared to the SI value (0.315) in more degraded stands which reflected low structural diversity. Consequently, the results revealed that, M and TD had the greatest influence on the SI values.
Investigating the SI index alongside the type of forest structure can provide valuable insights for managing forests. As a priority, conservation strategies should be implemented to prevent the further degradation of forests. In addition, this information could aid in implementing silvicultural practices to enhance structural diversity and promote sustainable forest development.

Keywords: deciduous forests, permanent sample plot, SI index, spatial patterns

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Introduction

Forest spatial structure is a key that strongly influences tree growth and ecological processes. Each tree contributes gradually to shaping forest structure, which in turn impacts forest dynamics (Aguirre et al., 2003; Pretzsch, 2009). The spatial distribution of trees is closely tied to ecological development, competition, species interactions, and habitat provision (Lin et al., 2011; Ramsay, 2015; Chen et al., 2018). The arrangement of tree species and their size distribution create variation in ecosystem functions, since all properties of a forest and the interaction between its components depend on the microstructure of the system (Pommerening & Grabarnik, 2019). Therefore, understanding the spatial structure helps us interpret the ecological processes behind the forest patterns.

Various structural diversity indices, based on species, size, and spatial location of tees have been developed for quantitative assessment of forest structure. These include aggregation indices and diversity metrics that provide affordable and replicable tools for characterizing forest heterogeneity (Krebs, 1999; Aguirre et al., 2003).

Individual-based method using four nearest-neighbor relationships is widely used for analyzing the spatial structure (Davies & Pommerening, 2008; Li et al., 2014; Dong et al., 2014). This method allow data collection from small plots, which can reflect stand-level patterns (Pommerening, 2006; Wang et al., 2016). Several studies have demonstrated that structural indices such as species mingling, size differentiation, and spatial distribution provide robust tools for forest comparison and management (Aguirre et al., 2003; Pommerening & Stoyan, 2008; Liu et al., 2021; Dong et al., 2022).

Several studies have focused on the applying forest spatial structure characteristics considering neighboring variables, with purposes such as forest management, comparative analysis, and reconstruction patterns. Aguirre et al. (2003) introduced key metrics such as mingling, size differentiation and absolute discrepancy for comparing complex forest structures. Pommerening and Stoyan (2008) showed nearest-neighbor summary statistics, even from small plots, can reliably capture broader spatial patterns. Liu et al. (2021) emphasized the influence of large trees on neighboring tree mingling and Dong et al. (2022) highlighted the use of structural indices to guide harvest planning and promote forest stability.

Iran's forests are distributed across three phytogeographical zones: Euxino-Hyrcanian, Irano-Turanian, and Saharo-Sindian (Sagheb Talebi et al., 2014). The Arasbaran forests, located in the Euxino-Hyrcanian zone in northwestern Iran, are among the country's most important ecological regions. Despite their protection status as a UNESCO Biosphere Reserve (Nahrli et al., 1999; Sagheb Talebi et al., 2003), Arasbaran forests face degradation due to overgrazing, tree cutting, road construction, and land use change (Yazdian et al., 1998; Sagheb Talebi et al., 2014). This has significantly altered forest structure and species composition.

Several studies in the Arasbaran region have assessed the spatial structure of specific species and stands. Abedi (2019) found high species mingling, but low diameter differentiation in *Acer campestre* L. populations. Ghanbari et al. (2019) showed long-term enclosed sites of *Taxus baccata* L. had greater diameter differentiation and distance to neighbors, along with a random spatial pattern. Sefidi et al. (2022) reported that degradation intensity shifted stand distribution from random to clumped, reduced species mixture, and altered structural diversity. Studies from similar Hyrcanian forests also showed that spatial patterns vary with forest development stages, in which tree distribution pattern was clumped in the initial and decaying stages of development, however, it was random in the optimal stage and the mingling index was lowest in the initial stage (Akhavan et al., 2012; Alijani et al., 2013). Similarly, Farhadi et al. (2019) found three types of natural deciduous forests (*Fagus, Fagus-Carpinus and Fagus-Acer*) in the Hyrcanian region that displayed predominately random tree distribution with low species mingling, though pure stands exhibited relatively higher tree densities.

Considering the ecological importance of Arasbaran forests, this study aims to assess and compare the spatial structure of six hornbeam– oak stands with different levels of degradation intensities i.e., more degraded and less degraded stands, using neighborhood-based structural indices related to species mingling, size differentiation, and spatial distribution. This research contributes to understanding how forest degradation affects structural heterogeneity and providing insights for sustainable forest management in this sensitive region.

Materials and methods

Study area

Mixed deciduous forests of Arasbaran span about 140,000 hectares, ranging in elevation from 256 to over 2,000 meters. Annual precipitation varies from 300 to 600 mm, with significant supplemental moisture from fog. The region hosts approximately 1334 plant species, including 97 tree and shrub species (Javanshir, 1992; Birang et al., 2001). The study was conducted in six forest stands in the Arasbaran region, consisting of three less degraded stands (LDS) and three more degraded stands (MDS) (Fig. 1).

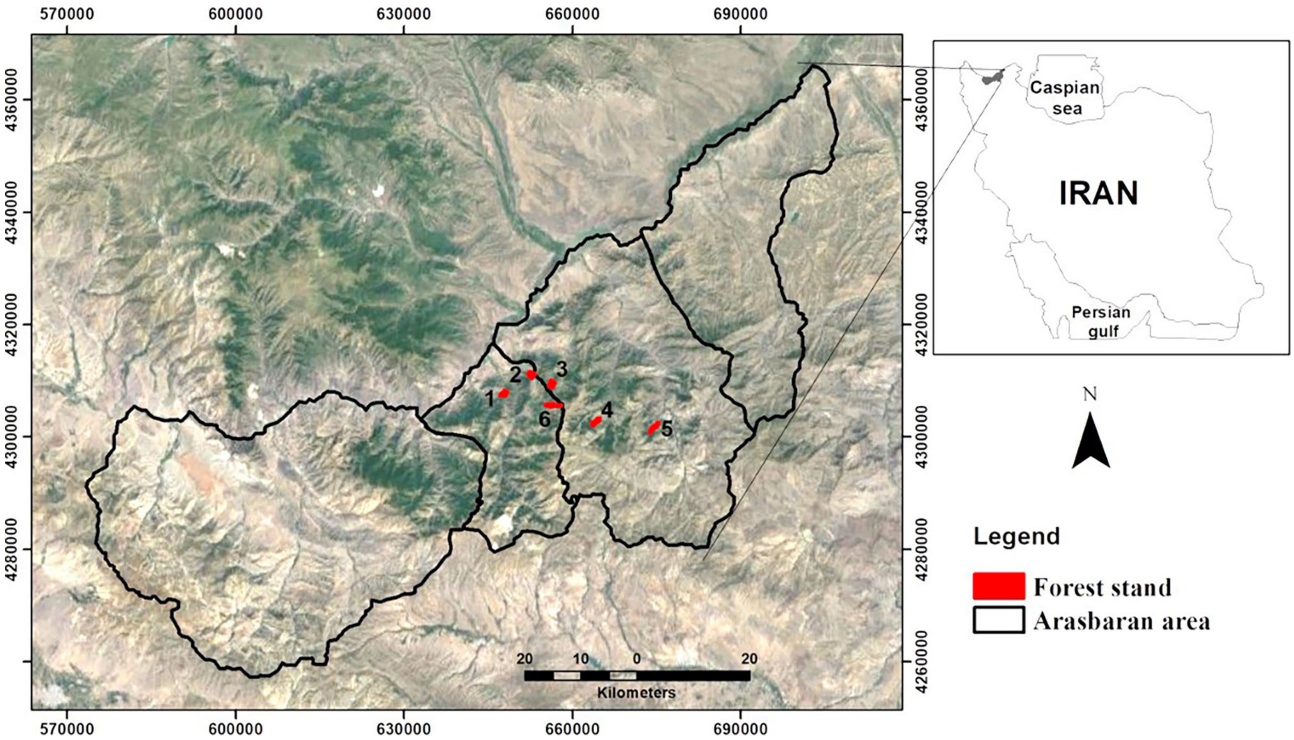

Fig. 1. Location of the six studied stands in the Arasbaran region (1, 2, and 3 are less degraded stands (LDS); 4, 5, and 6 are more degraded stands (MDS))

Table 1. The characteristics of the studied stands

Stands category & No.	Area (ha)	No. of sample plots	Range of slope (%)	Range of elevation (m)	Geographical aspect	Situation
LDS						
1	92.5	30	35–80	991–1390	N-W-NW	Distant from recreational areas, main roads and villages
2	93.5	30	30–75	1170–1700	N-NW-NE	
3	96	29	20–70	1354–1684	W-SW	
MDS						
4	86	29	15–50	1673–1932	W-N	Close to recreational area, main roads and villages
5	89	29	15–90	1446–1765	W-N-NW	
6	90	30	35–80	1380–1947	N-W	

Note: LDS: Less degraded stands; MDS: More degraded stands.

The six stands were selected concerning the various physiographic factors (altitude, slope, and geographical aspect), forest species composition, varying degradation intensities, and distance to villages, main roads, and recreation centers, based on the previous study in the Arasbaran region (Ostadhashemi et al., 2021) (Table 1).

Data collection

Data were collected from 177 permanent circular sample plots with an area of 300 m^2 (Alijanpour et al., 2018), arranged in a systematic grid of 150 × 200 m in the six forest stands. These stands primarily consisted of hornbeam (*Carpinus* sp.) and oak (*Quercus* sp.) tree species. In the MDS, these two species accounted for approximately 90% of the total species composition, while in the LDS, it was around 78%. The tree measurement variables include diameter at breast height (DBH ≥ 5), total height of all trees, species, number of coppice sprouts and standard trees. Trees were classified into DBH classes at 5 cm intervals. The classes were defined as follows: class 1: 5–7.5, class 2: 7.6–12.5, class 3: 12.6–17.5, class 4: 17.6–22.5, class 5: 22.6–27.5, class 6: 27.6–32.5 and class 7: 32.6–37.5. Furthermore, plot characteristics including slope percentage, main aspect, elevation (above sea level), and geographic coordinates were recorded at the center of each plot (Ostadhashemi et al., 2024).

Analysis method

The spatial structure of the six selected stands was assessed using various indices that consider tree size, species diversity, and tree coordinates, based on the four nearest neighbor method. In this method, a structural unit is defined by a reference tree and its four closest neighbor trees. We analyzed neighborhood-based parameters, which included species mingling (M), uniform angle (W), tree dimensions differentiation (T) concerning DBH (TD) and height (TH), distance to neighbors (D), and the O-ring statistic. These parameters all together, describe the spatial structure of a forest (Equations 1–5).

1. The M index is defined as the proportion of n nearest neighbors around each reference tree that belongs to a different species. m_j equals 0 when the reference tree (i) and its neighbor (j) are of the same species, and 1 when they are of different species. This index is divided into three possible values: low diversity for M < 0.3, medium diversity for 0.3 ≤ M <0.5, and high diversity for M ≥ 0.5 (Füldner, 1995; Aguirre et al., 2003).

$$M_i = \frac{1}{n}\sum_{j=1}^{n} m_j$$

$$m_j = \begin{cases} 1, \ species_j \neq species_i \\ 0, \ otherwise \end{cases}$$

where: M_i – mingling index; m_j – 1 or 0; i – reference tree; j – neighboring trees; n – total number of neighbors.

2. The W index measures the angles between the n nearest neighbors and a reference tree. w_j equals 1 if the measured angle between the reference tree and neighbor j (α_j) is smaller than α_0 and equals 0, otherwise. It is categorized into three values: W < 0.3 indicates a regular distribution, 0.3 ≤ W < 0.4 suggests a random distribution, and W ≥ 0.4 signifies a clumped distribution of trees (Gadow et al., 1998).

$$W_i = \frac{1}{n}\sum_{j=1}^{n} w_j$$

$$m_j = \begin{cases} 1, \ \alpha_j < \alpha_0 \\ 0, \ otherwise \end{cases} \qquad \alpha_0 = \frac{360°}{n+1} \qquad \alpha_0 = standard\ angle$$

where: W_i – uniform angle index; w_j – 1 or 0; i – reference tree; j – neighboring trees; n – total number of neighbors.

3. The T index measures the average size differentiation among all n neighbors. This index is categorized into three ranges: T < 0.3 indicates small size differentiation, 0.3 ≤ T < 0.5 indicates average size differentiation, and T ≥ 0.5 indicates large size differentiation (Füldner, 1995; Gadow, 1999). The differentiation in DBH and tree height were represented as TD and TH, respectively.

$$T_i = 1 - \frac{1}{n}\sum_{j=1}^{n} \frac{\min(m_i, m_j)}{\max(m_i, m_j)}$$

where: Ti – tree dimensions differentiation index; i – reference tree; j – 1 to n neighbor trees; n – the number of neighbors; m – any quantifiable tree size measure (DBH or Height).

4. The D index refers to the density of trees, ranging from low to high values. This scale refers to very dense to very sparse forest stands (Ruprecht et al., 2010).

$$D = \frac{1}{n}\sum_{j=1}^{n} s_{ij}$$

where: D – distance to neighbors index; n – the number of neighbors; i – reference tree; j – neighboring trees; S_{ij} – distance to 1^{th}, ..., n^{th} neighbor (m).

All analyses for calculation of M, W, TD, TH and D indices were carried out using Crancod Ver. 1.3 software.

5. The univariate O-ring statistic was used to analyze the spatial distribution pattern of trees. This method is similar to Ripley's K-function and the pair-correlation function g, which assess spatial patterns based on the average density of neighboring trees within a specified radius (r) (Equation 5). It then compares these patterns to a random distribution using the Monte Carlo simulation. When the O-ring graph is within the Monte Carlo envelopes, the tree distribution is considered random, above the upper envelope, the pattern is clumped, and below the lower envelope, the pattern is regular (Luis et al., 2008).

In this study, a univariate O-ring statistic was calculated for each group of stands by combining spatial patterns of 89 replicate plots for LDS and 88 replicate plots for MDS in Programita 2014 software. This was done in conjunction with 99 simulations using the Monte Carlo model (Luis et al., 2008; Illian et al., 2009).

$$O(r) = \lambda g(r)$$

where: $O(r)$ – O-ring statistic; λ – density (the number of trees per unit area); $g(r)$ – derivative of Ripley's K-function.

6. Finally, the complex structural diversity index (SI) was calculated using M, W, TD and TH indices, and their corresponding weights. The weights were determined based on the previously established relative importance of the indices and were set as follows: w_1 = 0.5, w_2 = 0.3, w_3 = 0.1, and w_4 = 0.1 (Pommerening & Stoyan, 2008; Pastorella & Paletto, 2013; Storch et al., 2018).

SI ranges from 0 to 1, where $S < 0.3$, $0.3 \le S < 0.4$, and $S \ge 0.4$ indicate low, medium, and high levels of biodiversity, respectively. This index is defined by Equation 6 as follows (McElhinny, 2005; Pastorella & Paletto, 2013).

$$SI = (M_i \times w_1) + (W_i \times w_2)\ (TD \times w_3)\ (TH \times w_4)$$

where: M_i – mingling index; W_i – uniform angle index; TD – tree dimensions differentiation index for DBH; TH – tree dimensions differentiation index for height; w_1, w_2, w_3 and w_4 – corresponding weights.

The NN1 method (nearest-neighbor edge correction method) was used to avoid the influence of the edge effects problem on the results of the spatial structure analyses and index calculations. The edge effect happened when the distance to the plot boundary was shorter than the distance to the n^{th} neighbor, then the nearest trees to the i^{th} tree may be located outside the plot (Pommerening & Stoyan, 2006).

The Kolmogorov-Smirnov test was conducted to assess the normal distribution of the data. An independent samples t-test was employed using SPSS 26 software, to compare the stands based on the average values of the spatial structural indices.

Results

The stands showed significant differences ($p < 0.05$) in all non-spatial characteristics of the studied stands, except for the percentage of standard trees. LDS had higher average values for DBH (11.7 cm), tree height (12.7 m), and basal area (17.7 $m^2\ ha^{-1}$). In contrast, it had a lower coppice percentage (45%) and density (1325 trees ha^{-1}) compared to MDS, which had 8.7 cm for DBH, 10.9 m for tree height, 13.5 $m^2\ ha^{-1}$ for basal area, 60% for coppice, and 1999 trees ha^{-1} for density (Table 2).

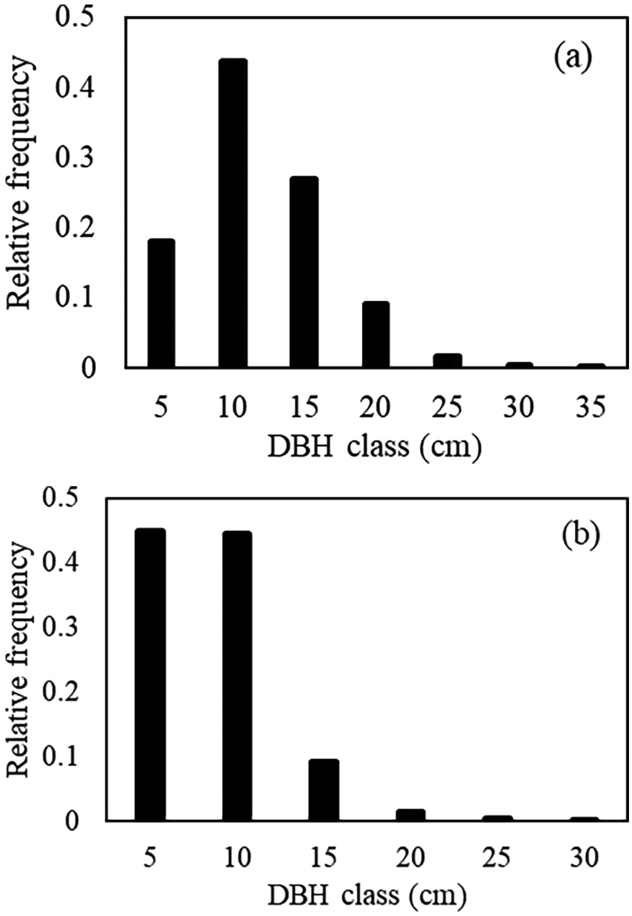

Fig. 2. DBH distribution of two groups of forest stands (a: LDS, b: MDS)

Table 2. Comparision of non-spatial characteristics of the two groups of the studied stands

Stand		N	BA	D	H	Standard (%)	Coppice (%)	Main Species
				LDS				
1		1090	19.9	13.1	15	63	37	A-B-C-D-E-F-G
2		1627	20.2	11.6	12	64	36	A-B-C-D-F-G-H
3		1259	13	10.4	11.3	38	62	A-B-C-D-F
Average		1325	17.7	11.7	12.7	55	45	
				MDS				
4		2434	12	7.6	9.3	33	67	A-B-C-D
5		1917	12.9	8.6	11	39	61	A-B-C-F
6		1645	15.7	10	12.4	49	51	A-B-C-D-F-G
Average		1999	13.5	8.7	10.9	40	60	
Statistical comparison	t	−7.03	4.24	8.62	6.27	−0.78	−8.37	
	df	176	176	176	176	176	176	
	Sig.	0.000**	0.000**	0.000**	0.000**	0.433^{ns}	0.000**	
	SE	95.31	0.977	0.371	0.325	1.807	2.22	

Note. LDS: Less degraded stands; MDS: More degraded stands; N: Number of trees per hectare; BA: Basal area ($m^2\ ha^{-1}$); D: mean DBH (cm); H: mean tree height (m); A: *Carpinus betulus* L.; B: *Quercus petraea* L. & *Q. macranthera* Fisch. & C.A.Mey.; C: *Acer campestre* L. & *A. monspessulanum* L. subsp. *Ibericum* (M.B) Yaltirik; D: *Cerasus avium* (L.) Moench.; E: *Sorbus torminalis* (L.) Crantz.; F: *Fraxinus excelsior* L.; G: *Ulmus glabra* Huds. & *U. minor* Miller.; H: *Taxus baccata* L.; SE: Standard error; **: Significant difference at P<0.01 and, ^{ns}: no significant difference.

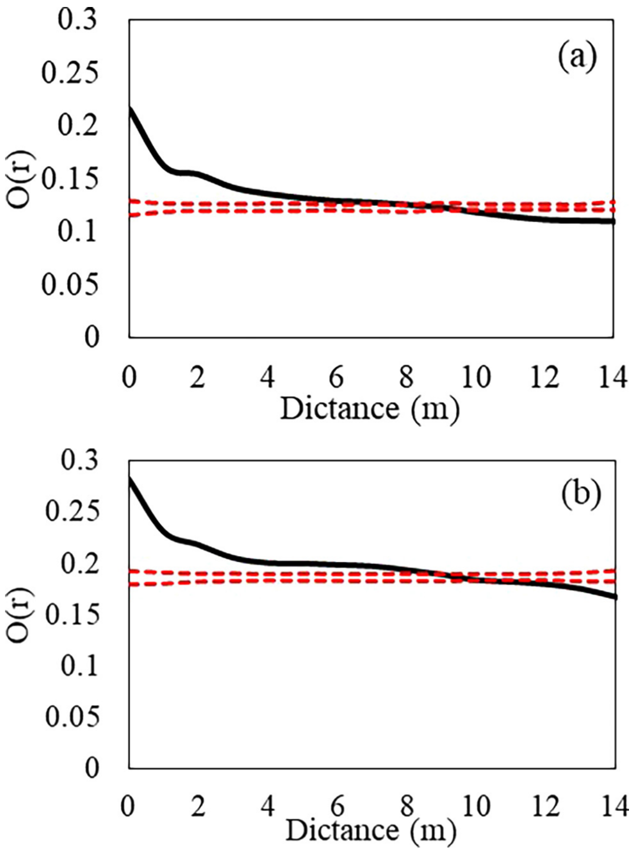

Fig. 3. Spatial distribution patterns of trees based on O-ring statistic (a: LDS, b: MDS, Dash line: Monte Carlo envelopes, Solid line: O-ring statistic)

The LDS (Fig. 2a) exhibited a wider range of DBH classes and nearly a bell-shaped diameter distribution compared to the MDS (Fig. 2b), with the highest numbers of small trees.

Based on the O-ring statistic results, the spatial distribution patterns of both groups of stands exhibited predominantly clumped distribution (Fig. 3). However, random distribution (Intersection point of the dashed and solid lines) was observed at distances of 7 to 10 meters in LDS (Fig. 3a) and 9 to 11 meters in MDS (Fig. 3b). This result indicates that the range of random distribution was broader in LDS compared to MDS. Beyond these distances, the distribution patterns were uniform.

Table 3 presents the results of the mean values of spatial structure indices for comparison of the two groups of forest stands with different degradation intensities.

The results indicated that the average values of M were 0.363 for LDS (medium species mixture category) and 0.226 for MDS (low species mixture category). The average W value was 0.53 for both groups, indicating a clumped distribution of trees. The values for TD were 0.268 for LDS and 0.236 for MDS. Furthermore, the TH values were 0.203 for LDS and 0.117 for MDS. Both groups of forest stands showed similar small size differentiation in DBH, and tree height, however, the LDS had higher TD, and TH values than the MDS.

The average tree density, indicated by mean values of distance (D), was 1.83 m for LDS and 1.51 m for MDS, which suggests that MDS has a higher tree density, meaning that the reference trees are closer to their neighbors compared to the LDS. Moreover, the two groups of forest stands demonstrated significant differences ($P < 0.05$) in the mean values of indices, except for the W index.

Figure 4 illustrates the distribution of different forest structure types (axis Y) based on SI index. In the LDS, 28% of the structure type was characterized by low species mixture, clumped spatial distribution, and small diameter and height differentiation (L.C.S.SM), followed by the structure type

Table 3. Comparision of the mean values of spatial structural indices of the two groups of the studied stands

Stand		No. of trees	No. of trees after edge correction	M	W	TD	TH	D
LDS								
1		1012	635	0.344	0.535	0.275	0.183	1.97
2		1464	875	0.35	0.553	0.277	0.199	1.63
3		1095	684	0.396	0.519	0.252	0.227	1.9
Average		–	–	0.363	0.535	0.268	0.203	1.83
MDS								
4		2110	1629	0.199	0.528	0.214	0.078	1.4
5		1658	1160	0.191	0.535	0.240	0.123	1.51
6		1471	1000	0.29	0.529	0.255	0.152	1.64
Average		–	–	0.226	0.53	0.236	0.117	1.516
Statistical comparison	t	–	–	4.580	0.188	3.648	12.253	5.720
	df			176	176	176	176	176
	Sig.	–	–	0.000**	0.851^{ns}	0.000**	0.000**	0.000**
	SE	–	–	0.029	0.007	0.007	0.006	0.068

Note. LDS: Less degraded stands; MDS: More degraded stands; M: Species mingling; W: Uniform angle; TD: Tree diameter differentiation; TH: Tree height differentiation; D: Distance to neighbours (m); SE: Standard error; **: Significant difference at $P < 0.01$ and, ^{ns}: no significant difference.

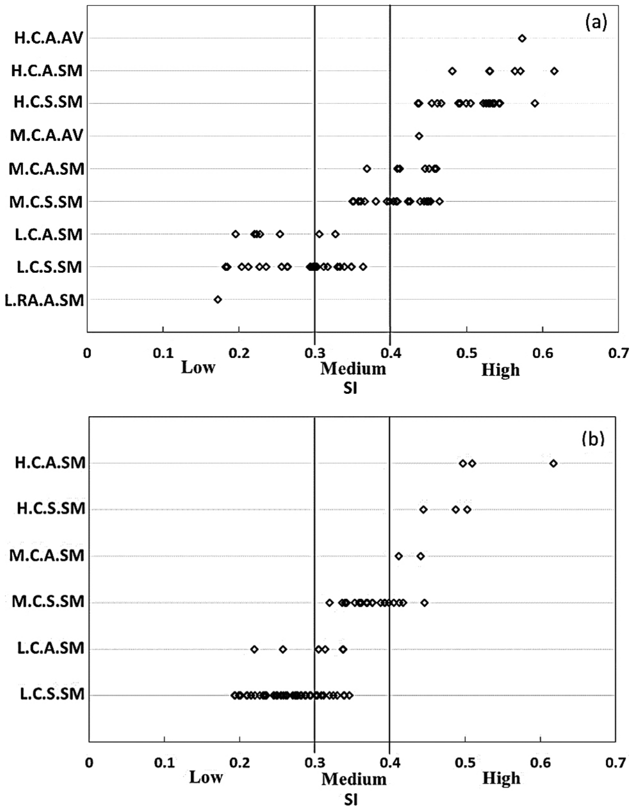

Fig. 4. Distribution of forest structur types based on the SI index value (a: LDS, b: MDS)

Note: L, M, and H refer to Low, Medium, and High species mixture, respectively (M-index); RA, and C denote Random, and Clumped tree distribution, respectively (W-index); S, and A indicate Small, and Average diameter differentiation, respectively (TD-index); SM, and AV represent Small, and Average height differentiation, respectively (TH-index).

with medium species mixture, clumped spatial distribution, and small diameter and height differentiation (M.C.S.SM) (23%), and another structure type with high species mixture, clumped spatial distribution, and small diameter and height differentiation (H.C.S.SM) (23%).

In the MDS, the most frequent structure type was defined by low species mixture, clumped spatial distribution, and small diameter and height differentiation (L.C.S.SM) (50%). The second most frequent structure type had medium species mixture, clumped spatial distribution, and small diameter and height differentiation (M.C.S.SM) (26%).

Moreover, the lowest SI value (0.17) was related to the low species mixture, random spatial distribution, average diameter differentiation, and small height differentiation structure type (L.RA.A.SM) in the LDS. In the MDS, the lowest SI value (0.19) was related to the structure type with low species mixture, clumped spatial distribution, and small diameter and height differentiation (L.C.S.SM).

Meanwhile, the highest complex structural diversity value (SI = 0.61) corresponded to the structure type with high species mixture, clumped spatial distribution, average diameter differentiation, and small height differentiation (H.C.A.SM) in both groups of stands. Hence, the average SI was obtained to be 0.394 and 0.315 in LDS and MDS, respectively, which reflected an approximate medium and low level of diversity.

Discussion

A quantitative evaluation of forest structure through spatial structural indices allows researchers to measure forest biodiversity. It is a crucial indicator for understanding the distribution of tree species, their growing conditions, and the competitive dynamics within a forest stand (Pommerening, 2002; Sterba & Zingg, 2006). In this study, we used frequent small sample plots rather than large plots. This approach provides more accurate estimations in quantifying variation, heterogeneity, and interactions between the four nearest neighbors, which contributed to the initial data for detecting forest structure within the entire forest stand.

To assess different aspects of the spatial structure of the two groups of less and more degraded forest stands (i.e., LDS & MDS), we used various indices related to species composition, tree size, and tree location (M, W, T, D, and O-ring). Previous studies have suggested that these spatial indices provide more reliable, accessible, and comprehensive insights compared to traditional methods, such as stand density, diameter distribution, and species composition. (Aguirre et al., 2003; Deng & Katoh, 2011; Akhavan & Hassani, 2023).

The results indicated that LDS had a higher average DBH and tree height but a lower density compared to MDS. The mixture in both types of stands was primarily influenced by two main species: hornbeam and oak, which made up 90% of MDS and 78% of LDS composition. These findings suggest that MDS experiences greater intra-specific competition, leading to higher density and frequency of the dominant species than LDS. In contrast, the lower frequency of the dominant species in LDS allows for the presence of other species, resulting in an increase in the M index. In addition, the M index indicated that 31% and 7% of all structural units (reference tree and four neighborhood tree) contained at least two different species ($M \geq 0.5$) in LDS and MDS, respectively. Previous researches confirmed that greater homogeneity of forest stands significantly reduces M index (Bettinger & Tang, 2015; Pommerening & Uria-Diez, 2017).

The horizontal distribution patterns implied the aggregation distribution in both stands. However, the LDS had a wider range of distances related to the random distribution. Based on the O-ring statistic and approximated plot radius (r = 11m), we found that in 55% of the intervals for LDS and 73% for MDS, the tree distribution was clumped. It was evident that the distances between trees were smaller than expected by randomly distributed. This may result from various factors, such as, groups of young trees by coppices form, as a result of human intervention and a limited regeneration dynamic in small gaps, which aligns with findings from previous studies (Wiegand & Moloney, 2004; Law et al., 2009; Alijanpour & Mahmoudzadeh, 2007; Sefidi et al., 2022). Sefidi et al. (2022) confirmed that human activities have altered the structure of forest stands and caused regeneration problems due to the cutting of small-diameter trees and grazing in the Arasbaran forests. Similarly, Alijanpour and Mahmoudzadeh (2007) reported destructive factors, including tree cutting, branching, and over grazing in these forests. Moreover, the index of W indicated a clumped distribution patterns within the structural units for both groups. The dominance of hornbeam and oak species and their ability to produce coppice sprouts may contribute to the formation of groups of the same species, consequently in a pronounced clumped pattern, as also noted by Dong et al. (2022).

Other results from this study indicated low TD and TH in both groups, indicating homogenous trees in terms of dimensions that are confirmed by the high percentage of young coppices and the high number of trees in the smaller DBH classes (the frequencies of 63% and 89% were observed in the DBH classes up to 10 cm for LDS and MDS, respectively). This issue may reflect forest exploitation for charcoal production in recent decades in the Arasbaran region, which was supported by Ghalandarayeshi et al. (2017) that noted disturbances over the past decade caused a bell-shaped diameter distribution of ash trees in a semi-natural forest in Denmark.

Our results confirmed the high tree density based on the D index in both groups. However, we found that increased space (higher D value) between reference trees and their neighbors in the LDS led to reduced competition and tree density, which consequently enhanced tree DBH and height growth, resulting in higher values of TD and TH indices in the LDS. In addition, LDS with a greater M index tended to exhibit larger trees and a more size differentiation index, which aligns with the M-size hypothesis proposed by Pommerening et al. (2020). This suggests that trees surrounded by diverse species tend to grow larger.

The results also showed significant differences among all indices in the stands, except for the W index. This indicated that despite the same physiographic conditions, forest type, and species composition, there were differences in their structures that may have been due to different degradation intensities. Mishra et al. (2004) confirmed that anthropogenic disturbance can affect the plant diversity and the structure of forest stands.

In General, structural diversity can be measured using many different indices or summarized into a single index value such as FSI, SCI, etc. (Beckschäfer et al., 2013; Storch et al., 2018; Zhao et al., 2022; Liu et al., 2023). The use of different indices provides more information about detailed responses between individuals, and therefore, the structural diversity performs as an indicator to compare different tree populations. Liu et al. (2023) determined the priority and weight of seven spatial structure indices for mixed forest stands using the homogeneity structure index. The importance ranking of the parameters was as follows: neighborhood comparison, competition, W, M, openness ratio, forest layer difference, and crowding, with corresponding weights of 0.29, 0.14, 0.11, 0.08, 0.12, 0.06, and 0.20, respectively.

In this study, a complex diversity value was used to reveal the differences in structural diversity between the plots in two groups of stands. According to the results, the LDS exhibited a higher structural diversity (SI = 0.394) than the MDS (SI = 0.315). In the LSD, 52% of the plots, demonstrated high structural diversity, while it was only 13.5% in the MDS. Previous studies reported that the value of SI = 0.479 is an acceptable structural diversity for a maple forest stand (Abedi, 2019), and SI = 0.5 indicates high structural diversity in a low-degraded stand in the Arasbaran region (Sefidi et al., 2022).

Furthermore, the evaluation of the SI index value, together with the different forest structure types in the study groups at the same time, revealed that in the plots with high structural diversity in LDS, 47% had a stand structure with high species composition, clumped spatial distribution, and small diameter and height differentiation (H.C.S.SM).

In addition, among the plots with high structural diversity in MDS, 50% displayed two types of stand structures: the first type was characterized by high species composition, clumped spatial distribution, small diameter, and height differentiation (H.C.S.SM), and the second type had high species composition, clumped spatial distribution, average diameter differentiation, and small height differentiation (H.C.A.SM).

Consequently, it can be concluded that the variables had the most effectiveness in increasing structural diversity in both groups were related to species composition and tree diameter differentiation which were more reflected in MDS. The high density of individuals and the significant percentage of coppices resulted in a substantial reduction in tree diameters and consequently leading to a decrease in the structural diversity in MDS.

Our results clarified the importance of species mixture for forest structural diversity, as supported by Graz (2004). Furthermore, Pastorella and Paletto (2013) declared that certain levels of biodiversity may correspond to forest structures. They suggested that the analysis of forest stands should consider both values of diversity index and description of the forest stand.

Our findings align with earlier work (Akhavan et al., 2023) showing that spatial and quantitative indices of the forest structure can play an important role in developing conservation strategies, making decisions and implementing silvicultural practices. Spatial structural indices, can be used to identify critical areas and guide silvicultural interventions through the focus on highly effective factors such as species composition and tree dimensions. Improving the current status of these variables such as reducing tree density by removing some coppice sprouts and selective harvesting to reduce intra- specific competition, promotes tree growth, and creates opportunities for new species establishment. Such approaches not only preserve species composition, but also contribute to the stability and ecological functioning of the forest and sustainable forest development.

Conclusion

Monitoring the structural changes of forest stands using permanent sample plots can be beneficial, since provide important information for forest structure-based management plans and interventions. Our findings confirm that determining the SI index alongside the forest structure type can provide valuable insights for forest management. As a further study, developing a thinning model could be recommended for this region.

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