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Analyzing the Biological and Structural Diversity of Hyrcanian Forests Dominated by *Taxus baccata* L.

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Abstract: The Hyrcanian Forests, well-known for its World Heritage site in the South Caspian region of Northern Iran, are refugia for a special tree flora. Some areas in particular feature a concentration of large and numerous trees of *Taxus baccata*, a species that has attracted the interest of many researchers given its medicinal importance. The objective of this study was to analyze the biological and structural features of these unique ecosystems based on three large tree-mapped field plots using new methods. We developed a species abundance distribution and three species–area relations, and analyzed the small-scale structural patterns of each of the 15 tree species that occur in the plots. Species-specific details are presented for each of the three field plots, including the tree densities and average tree sizes, as well as the associated structural indices "species mingling", "dominance", and "size differentiation". This includes non-linear relationships between tree density and neighborhood mingling, and between the average tree size and neighborhood dominance, and a linear relation between the neighborhood dominance and the mean neighborhood differentiation. Based on the findings, we recommend the use of these methods and indices for analyzing the structure of natural forests in other regions of the world.

Keywords: *Taxus baccata*; South Caspian forests; neighborhood structure; species abundance distribution

1. Introduction

Forest ecosystems are characterized by composition, function, and structure [1]. The structure of a forest determines processes and interactions among biotic and abiotic elements [2] and plays an important role in regulating the evolution of a forest including the relationship among living and dead trees [2,3]. Specific processes, such as competition and facilitation among species, as well as environmental disturbances can affect the structure of a forest. Structural change in turn affects the evolution of the system [4]. Studying the structural properties of a forest is therefore one of the most important prerequisites for understanding and managing forest ecosystems [5]. Forest ecosystems are continuously changing due to environmental disturbances, as well as harvesting and tending operations. Knowing the features and complexities of forest structure guides us to a better understanding, and provides appropriate solutions for their sustainable management. Understanding the interdependencies between natural processes and human activities and the effects on forest structure is essential for management and conservation, particularly for endangered species

[6–8]. For description and comparison of the spatial structures of the forest stands, numerous qualitative and quantitative indices have been developed [9–16]. Some of these indices have been widely applied in forest research. Many are related to spatial relationships between neighboring trees.

The Hyrcanian Forest, a World Heritage site, extends from Talish in the Republic of Azerbaijan to the Golestan province in Iran, covering the northern slopes of the Alborz Mountains to the south of the Caspian Sea. These ancient forests covered most of the Northern Temperate region, retreating during the Quaternary glaciations and expanding again as the climate became milder. The Hyrcanian forests are known as refugia for many Arcto-Tertiary relicts, which have been classified as Hyrcanian and Euxino-Hyrcanian elements [17]. Some species of the Hyrcanian forests are of Indo-Maleysian origin. Many descendants of the Arcto-Tertiary flora occur now in the xerophytic habitats of the Irano-Turanian parts of Iran. The current knowledge on the flora of this unique region is presented in the Flora Iranica [18] and specific contributions published in the Iranian botanical journals *The Iranian Journal of Botany* and *Rostaniha.* Numerous floristic studies have been published, mostly relating to protected areas and national parks in the region [19–22]. The tree flora of the Caspian forests includes Hyrcanian endemics (e.g., *Parrotia persica* (DC.) C. A. Mey., *Acer velutinum* Boiss., and *Quercus castaneifolia* C. A. Mey.), Omni-Euro-Siberian species (e.g., *Carpinus betulus* L., *Fraxinus excelsior* L., and *Sorbus torminalis* (L.) Crantz.), and Euro-Siberian elements (e.g., *Taxus baccata*, *Alnus glutinosa* (L.) Gaertn., *Ulmus minor* Mill) [23]. *Taxus baccata* is a rare native species in the forests of northern Iran. This species is observed from Astara in the west of the Hyrcanian forests to Gorgan in the east of the Hyrcanian forests, either as scattered small groups (in Vaz and Gazo in the central parts of the Hyrcanian forests) or as large stands (Afratakhteh and Siah-Rudbar).

The genus *Taxus* includes 73 species names of which the majority are synonyms. Nine species have been accepted in *The Plant List* which are distributed mostly across the northern temperate region [24]. One of these is *Taxus baccata* (Figure 1), which prefers cool, humid, and high-altitude habitats [25]. Studies on *Taxus baccata* have attracted the interest of many researchers around the world, given its medicinal importance. Extracts are used in traditional medicine and for the treatment of cancer [26,27]. Although the species is widely distributed throughout the world, it is regarded as a rare and valuable resource [28,29]. Illegal cutting of yew trees, their regeneration failure, herbivory by deer, unfavorable soil conditions, and loss of genetic diversity are major causes of the decline of the species [7,30].
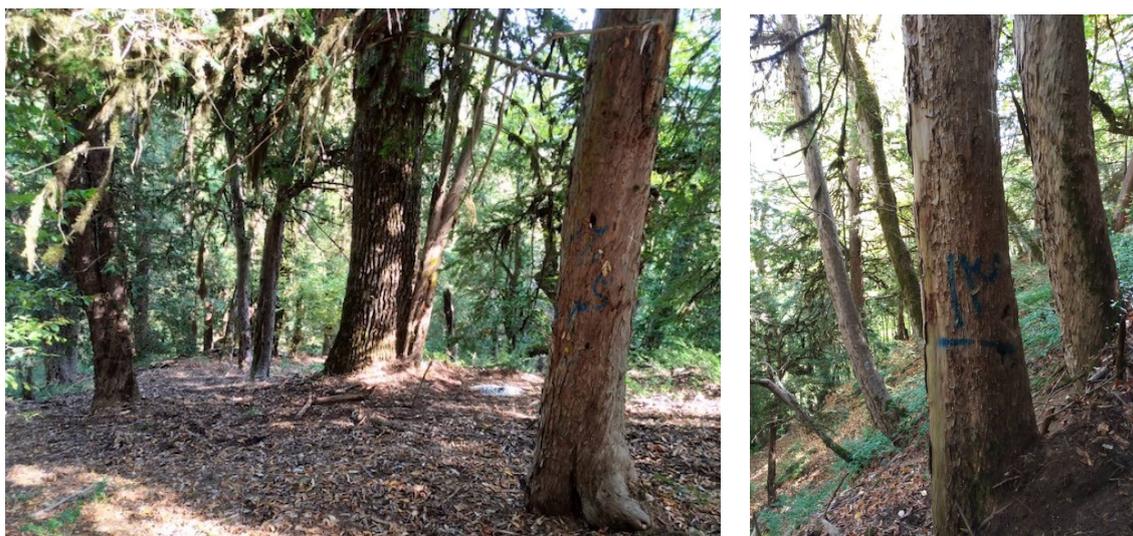

Figure 1. Impressions of the field plots with large *Taxus baccata* and *Quercus castaneifolia* trees assessed in the course of this study (Photos by Seyed Jalil Alavi).

Taxus baccata is an important tree species in northern Iran, and a number of studies relating to the environmental conditions, regeneration, and structural characteristics of *Taxus baccata* communities have been published by Iranian scientists. Community composition and structure of *Taxus baccata* stands were studied by Ghanbari et al in three habitats of Kalaleh, Viqan, and Korn in the Arasbaran floristic region [31]; by Waez-Mousavi and Maghsoudlou Nezhad in the Tuskistan Valley in the northern Iran [32]; and by Esmailzadeh et al. in the Afratakhteh forest reserve [33].

Several studies report on the distribution of *Taxus* and its relationship with edaphic and topographic factors in the Hyrcanian forests. Habibi and Lesani examined the soil status and quality of *Taxus* forest stands in two regions in Aliabad and Gorgan, and concluded that *Taxus* trees are not very sensitive to the soil type [34]. Zand Akbari has shown that *Taxus* is sensitive to soil and atmospheric moisture. The species prefers moist soils and sedimentary rock. It does not grow well in poor and dry soils. Ahmadi *et al.* studied the relationship between soil physical and chemical properties and its mineral nutrition by the yew tree in the Vaz research forest [35]. The results showed that yew trees grow on different soil types. The soils had good drainage and were rich in organic matter. In general, the amount of nutrients in the soil is related to the amount of nutrients absorbed by *Taxus* trees [36]. Mohajer Orsaji examined the most important effect of environmental characteristics on the quantity and quality of two *Taxus* stands in the Siah-Roudbar region in Golestan province. The results showed that in both stands, the regeneration and quantity and quality of the trees depend on factors, such as light, humidity, slope, and aspects (especially north-facing slopes). The species was found to be indifferent to the chemical soil properties. In areas with an annual rainfall of more than 1000 mm, it grows mostly on shallow rendsina, as well as on acidic soils [37]. Esmailzadeh et al. studied the *Taxus* forests of Afratakhteh. Studying the correlation between physiographic factors (altitude, slope, and aspect) with *Taxus* communities showed that the distribution of these communities is affected by the slope [33]. The study of Ebady and Omidvar, and Alemi et al. showed that *Taxus baccata* prefers northern and humid aspects [38,39]. Alavi et al. studied the importance of climatic, topographic, and edaphic variables on the distribution of yew species in the Hyrcanian forests. Their study showed that among the bioclimatic variables, the mean temperature in the driest season of the year and the precipitation in the hottest season of the year had the greatest effect on the distribution of the *Taxus* trees. Edaphic variables, such as organic carbon, sand percentage, cation exchange capacity, elevation above sea level, and slope percentage, were other important factors influencing the distribution of *Taxus baccata* in the forests of northern Iran [40,41].

It should be noted that endangered tree species often play important ecological roles in forests. The number of endangered tree species has been reported to be increasing worldwide due to climate change. Therefore, to sustainably manage the ecosystems, effective conservation strategies need to be implemented which should be based on studies of forest structure. Studies of small-scale patterns in forests are still relatively rare [42]. The objective of this study is to analyze biological and small-scale structural patterns of diversity in three large field plots. Particular objectives are: 1. To demonstrate particular applications of structural analysis based on the neighborhood constellations of individual trees; 2. to identify the relationships between the relative frequency and mean size of a particular species and the structural pattern in its vicinity; 3. to present an approach for making estimates of species richness that facilitates comparisons among different plot sizes; and 4. to raise awareness among the scientific community of a unique forest area in Iran, and thus to make a contribution to more effective conservation of this important natural heritage. This research highlights the characteristics of two forest reserves and suggests some implications for conservation of the *Taxus* communities.

2. Materials and Methods

2.1. Study Areas

Three large field plots with mapped trees, dominated by *Taxus baccata*, were selected for the study. The plots are located in the Golestan province in Iran. Figure 2 shows the location of the study areas in the eastern part of the Alborz Mountains.
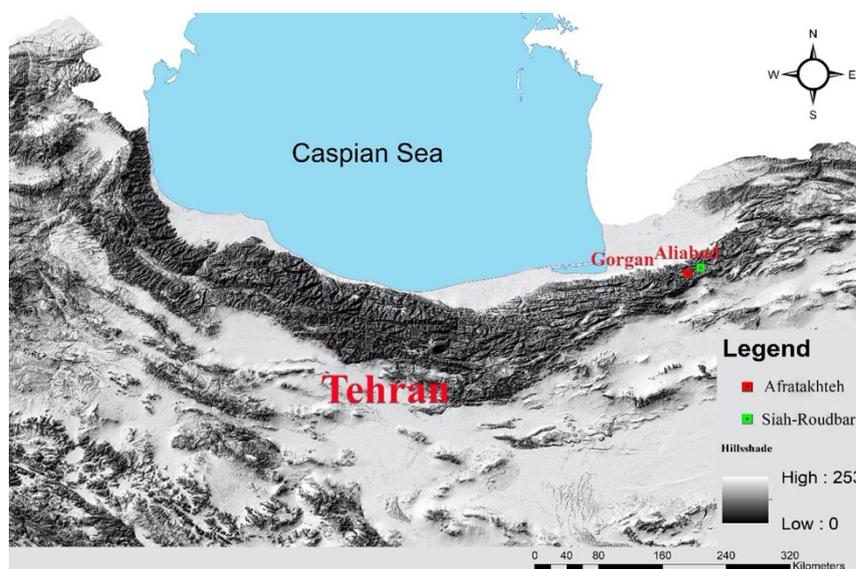

Figure 2. Location of the study areas in the eastern part of the Alborz mountains.

Two plots were established in the Afratakhteh forest reserve about 60 km southeast of Gorgan in the vicinity of the village Afratakhteh, near Aliabad Katoul. A third plot was established in the Siah Roudbar forest about 22 km from Aliabad Katoul. All yew trees with a diameter at breast height (dbh) greater than 2.5 cm and other tree species with a dbh greater than 7.5 cm were mapped using a TP360 Laser Rangefinder.

The study areas represent a rare remnant habitat in the Hyrcanian forests where *Taxus baccata* trees grow in dense and sometimes pure stands. This feature makes the study areas unique. Due to their particular status, these habitats were proclaimed as specially protected forest reserves in 1992. Because of the rugged topographic conditions and steep slopes, the study areas have survived in an untouched part of the Hyrcanian forests. Figure 3 presents the maps of the three field plots that were used in the analysis. The plot outlines were cropped to a rectangular shape. This resulted in a minor loss of data but greatly facilitated analysis.

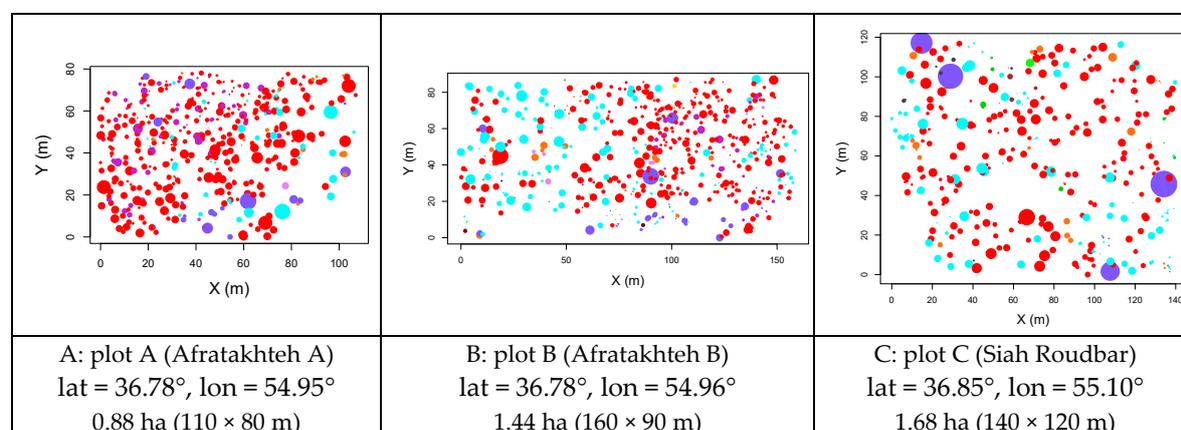| A: plot A (Afratakhteh A) lat = 36.78°, lon = 54.95° 0.88 ha (110 × 80 m)	B: plot B (Afratakhteh B) lat = 36.78°, lon = 54.96° 1.44 ha (160 × 90 m)	C: plot C (Siah Roudbar) lat = 36.85°, lon = 55.10° 1.68 ha (140 × 120 m)

Figure 3. The three plot maps (**A**: Afratakhteh A, **B**: Afratakhteh B and **C**: Siah Roudbar) with the latitude (lat) and longitude (lon) of the plot centers, plot dimensions, and total areas; the most

abundant tree species is *Taxus baccata* shown in the red color. Other prominent species are *Carpinus betulus* (light blue), *Carpinus schuschaensis* H. Winkl. (violet), *Tilia rubra DC.* (bisque), *Acer laetum* C. A. Meyer (chocolate), and *Quercus castaneifolia* (blue).

The Afratakhteh and Siah Roudbar forests are classified as protected areas, and thus enjoy a high degree of protection. The general slope in Afratakhteh is 40–45%, and the aspect is mainly northeast. The average annual precipitation in this region is about 950 mm and the average annual temperature is 10.3 °C [33].

The three plots have different areas, which precludes direct comparison based on the common measures of alpha diversity. We identified biological patterns of diversity using the species abundance distribution for all plots combined. We also developed a species area relation separately for each plot. Structural patterns of diversity were analyzed using specific neighborhood constellations for each tree species, including the relative dominance, spatial mingling, and the variation of tree diameters in the vicinity of a particular reference species. Based on the results, we evaluated the relationships between certain parameters commonly assessed in a standard forest inventory (relative tree abundance, mean dbh) and the neighborhood constellations (species dominance and mingling).

2.2. Biological Diversity

Meaningful assessments of forest density, biomass production, and carbon storage are expressed for a standard unit of area, i.e., one hectare. Because the relation between these quantities and forest area is linear, a 15-m^2 basal area on 0.5 ha is equivalent to 30 m^2 per ha. However, 10 species on 3 ha is not equivalent to 20 species on 6 ha, because the relation between the number of species and the forest area is non-linear. We are unable to express richness per ha directly from a sampled area. Accordingly, it is necessary to create a common basis for comparing the species richness among different ecosystems.

2.2.1. Measuring Tree Species Richness

To create a common basis for comparing the species richness of different ecosystems, it is necessary to estimate the number of species for a standard unit of area. When Smax = 1, Amin = α. Our estimate of α = 483.44 m^2 is very close to the area of 500 m^2 defined by the Food and Agriculture Organization (FAO). This finding is of great practical value because it implies that sample plots should not cover an area less than α. This is an important new finding that complements traditional species–area relations.

The three Hyrcanian forest plots include 15 species (14 of which are Angiosperms) in 10 families. The differences in micro-site conditions generally increase with area and accordingly, the variety of species that can be supported generally increases with an increasing contiguous area [43,44]. The three plots have different areas, thus direct comparison of the α-diversities is not possible. To make the plots comparable in terms of richness, we developed a relation between the contiguous plot area and the number of species in each plot. To derive a species–area relation, sample plots of increasing size were assigned to random positions within the field plot. The number of species was then determined within each sample. The sampled area and associated number of species were used to derive a species–area relationship for the whole plot. The following functions are among the popular ones for estimating a species–area relation [23–26]: the Asymptotic function: $S = a \cdot (1 - \exp(-b \times A))^c$; the Power function: $S = a \cdot A^b$; the Monod Function: $S = a \cdot A/(1 + bA)$.

Asymptotic functions are appropriate in very large plots where all species are likely to be captured by the samples. The power function is more suitable for small plot sizes where the maximum number of species is unknown. The three Hyrcanian plots are large, but not large enough to capture all species. The following function, proposed by Monod, were therefore employed to estimate the species–area relation (SAR):

$$S = a \times A/(1 + bA), \tag{1}$$

where a, b are empirical parameters; S is the number of species; and A is a contiguous forest area (m²). Equation (1) has the following properties: (1) When $A = 0$, then $S = 0$; (2) S increases with increasing A, until an asymptotic value of S (S_{max}) is reached; and (3) the estimated maximum number of tree species equals a/b, which is a useful property. The second derivative of Equation (1) gives:

$$S'' = \frac{-2ab}{(1+bA)^3}. \tag{2}$$

The model has no inflection point. To obtain the minimum area A_{min} of the community that should include all species, we set S'' close to zero using a very small threshold. This relationship, which has been referred to as one of the few fundamental laws in ecology [45], estimates the number of species for any area, and thus permits a comparison of species richness among the three plots.

2.2.2. The Species Abundance Distribution

The species abundance distribution (SAD), believed to be one of the most ubiquitous patterns in ecology, describes the abundances of all species recorded within a forest community of interest. The SAD may explain processes of community assembly [46], help to predict the response to disturbance [47], and suggest appropriate measures of biodiversity conservation and management [48]. The following function was used to estimate the species abundance distribution of the three *Taxus baccata* plots combined:

$$F = a \times S^b, \tag{3}$$

where F is the frequency of species S (ordered from 1 to 15, according to their frequency).

2.3. Structural Diversity

Information about structural diversity presents a useful complement to the purely biological analysis of species richness and abundance distributions. One way to characterize forest structure is to use nearest neighbor statistics for individual tree species. We used indices of mingling, dominance, and size differentiation to describe the specific neighborhood constellations of each individual species. These three measures of species-specific structural diversity are defined in Table 1 [13,49].

Table 1. Measures of species-specific structural diversity.

Mingling (M)	Dominance (D)	Size Differentiation (T)
Mean heterospecific fraction of trees among the k nearest neighbors of a given tree i.	Mean fraction of n nearest neighbors with a dbh < (dbh of the reference tree).	Mean of the ratio of smaller and larger tree sizes u of the k nearest neighbors subtracted from one.
$M_i = \frac{1}{k}\sum_{j=1}^{k} 1(species_i \neq species_j)$	$D_i = \frac{1}{k}\sum_{j=1}^{k} 1(dbh_i > dbh_j)$	$T_i = 1 - \frac{1}{k}\sum_{j=1}^{k} \frac{min(u_i, u_j)}{max(u_i, u_j)}$

We used edge correction to ensure that estimates were unbiased: The distance to the plot boundary of each reference tree must be greater than the distance to its 4th neighbor. The three variables represent a system for characterizing high-resolution structural variation in a consistent set, where all the variables assume values in the interval (0, 1). Mingling defines the degree of spatial segregation of the tree species in a forest [13,50]. Dominance measures the size dominance of the reference tree in relation to its four nearest neighbors [51]. Size differentiation measures the difference in tree size between the reference tree and its four nearest neighbors [13,49].

The dbh coefficient of variation (CV) of all trees within the neighborhood group (including the reference tree) is also known as the relative standard deviation. This variable was also assessed and compared with the differentiation variable T. We also evaluated the relationships between variables that are normally assessed in routine forest inventories (mean dbh; number of trees per ha) with the neighborhood structures.

In addition, the spatial pattern of the community of forest trees was evaluated by calculating the angles between the vectors joining a particular reference tree to its n nearest neighboring trees [52]. The variable, known as the uniform angle index, was defined as follows:

$$W_i = \frac{1}{k} \sum_{j=1}^{k} 1(\alpha_{ki} < \alpha_0) \tag{4}$$

with four neighbors, W_i can assume five values (0.0; 0.25; 0.5; 0.75 and 1.0). For the uniform angle index to be independent of the number of neighbors, the standard angle α_0 should be set equal to $360/(n+1)$, where n refers to the number of neighbors of a selected reference tree i.

3. Results

3.1. Species Richness per Hectare

The parameters a and b of the Monod model (Equation (1)) for estimating the species–area relation are shown below for each of the three field plots (Table 2).

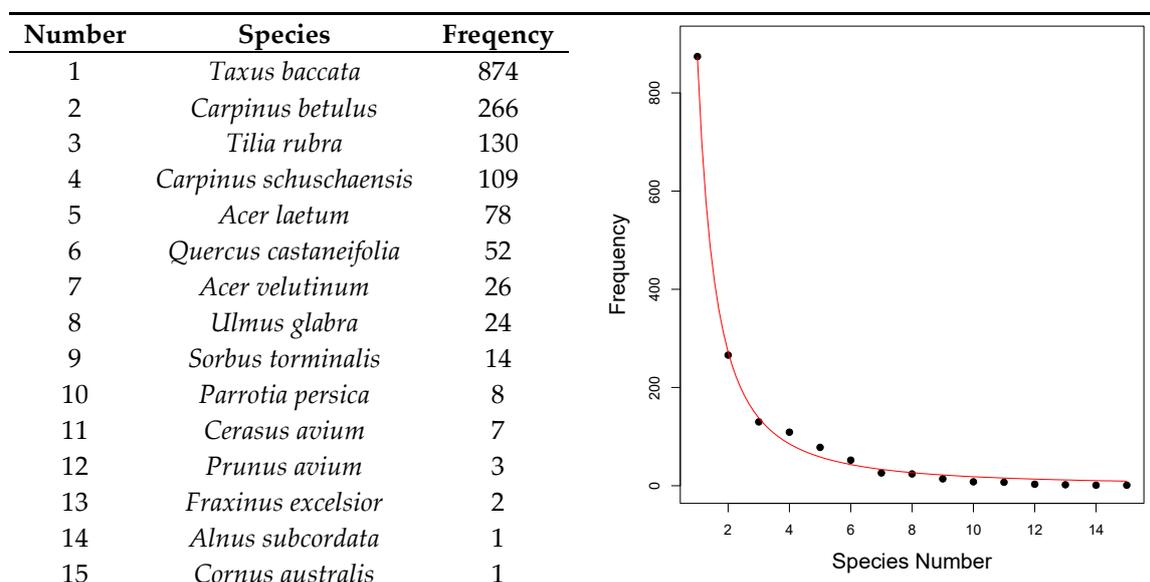**Table 2.** Parameters of the Monod model for estimating the species–area relations.

Plot	a	b	Observed Number of Species per ha	Maximum Number of Species (a/b)
A	0.0569	0.00639	8	8.9
B	0.0411	0.00379	8	10.8
C	0.0254	0.00254	10	10.0

These parameters can be used to estimate the number of species for any area, and thus make species richnesses comparable among different plot sizes. For areas of 10,000 m², for example, the estimates are A = (0.0569 × 10,000)/(1 + 0.00639 × 10,000) = 8.77 species per ha; B = 10.57 species per ha; and C = 9.62 species per ha, slightly less than the maximum number of species. The theoretical (and practical) implication of this approach is not the specific result, but the method. The relationship between plot area and species richness is non-linear. The diversities of different plot sizes are therefore not directly comparable. Our method of comparing species richness for any arbitrary plot size is of general interest, for example, in global assessments of biodiversity when the empirical data base includes field plots with different areas.

3.2. The Species Abundance Distribution

Species abundance curves provide information about how communities differ in the way they are organized. The species abundance distribution generally takes a curve shape that is defined by many rare species and a few common ones [46,53]. Table 3 presents the observed frequencies of the 15 tree species, which were assessed in the three field plots combined, and a graph of the fitted SAD. The three forests are dominated by *Taxus baccata*. *Carpinus betulus* is also very abundant with 266 individuals. Two species, *Parrotia persica* and *Cerasus avium* (L.) Moench, are rare with eight and seven individuals while four species are very rare with only one, two, or three individuals (*Prunus avium* L.Gean, Mazzard, *Fraxinus excelsior, Alnus subcordata* C. A. Mey., and *Cornus australis C. A. Mey.*).

Table 3. Species abundance distribution of the three Hyrcanian forest plots combined. Two species (*Taxus baccata* and *Carpinus betulus*; species 1 and 2) are very abundant, two species are rare (*Parrotia persica*; *Cerasus avium*, species 10 and 11), and four species are very rare (*Prunus avium*; *Fraxinus excelsior*; *Alnus subcordata*; *Cornus australis*; species 12 to 15).

Number	Species	Freqency	
1	*Taxus baccata*	874	
2	*Carpinus betulus*	266	
3	*Tilia rubra*	130	
4	*Carpinus schuschaensis*	109	
5	*Acer laetum*	78	
6	*Quercus castaneifolia*	52	
7	*Acer velutinum*	26	
8	*Ulmus glabra*	24	
9	*Sorbus torminalis*	14	
10	*Parrotia persica*	8	
11	*Cerasus avium*	7	
12	*Prunus avium*	3	
13	*Fraxinus excelsior*	2	
14	*Alnus subcordata*	1	
15	*Cornus australis*	1	

The shape of the species abundance distribution is influenced by the degree to which common species dominate the community, and by the number of very rare species [54]. Communities that are strongly dominated by one or a few species often have low species diversity overall. Our results confirm this observation.

3.3. Species Table

Table 4 presents species-specific details separately for each plot. The information includes parameters that are assessed in routine forest inventories (mean dbh, trees per ha, and basal area (BA) m²/ha) as well as the means of the structural indices mingling (M), dominance (D), and size differentiation (T).

Table 4. Species-specific detail presented separately for each of the three field plots.

Plot	Species	Family	Mean dbh	Trees per ha	BA m²/ha	M	D	T
	Acer laetum	Sapindaceae	17.9	9	0.16	0.89	0.27	0.42
	Carpinus betulus	Betulaceae	26.3	33	1.65	0.82	0.51	0.37
	Carpinus schuschaensis	Betulaceae	26.3	68	2.83	0.73	0.52	0.38
	Quercus castaneifolia	Fagaceae	45.3	12	1.52	0.73	0.68	0.37
A	*Sorbus torminalis*	Rosaceae	15.2	6	0.12	0.92	0.25	0.44
	Taxus baccata	Taxaceae	31.0	313	17.71	0.27	0.55	0.34
	Tilia rubra	Malvaceae	42.5	7	0.84	0.87	0.53	0.41
	Ulmus glabra	Ulmaceae	7	1	0	1.00	0.00	0.84
		total		449	24.83			
	Acer laetum	Sapindaceae	22.1	17	0.61	0.64	0.47	0.61
	Carpinus betulus	Betulaceae	28.8	41	3.25	0.59	0.55	0.47
	Carpinus schuschaensis	Betulaceae	26.3	68	3.72	0.74	0.42	0.36
	Quercus castaneifolia	Fagaceae	44.7	16	2.58	0.65	0.60	0.46
B	*Sorbus torminalis*	Rosaceae	15.2	6	0.16	0.89	0.46	0.35
	Taxus baccata	Taxaceae	31.8	341	26.89	0.33	0.56	0.38
	Tilia rubra	Malvaceae	40.2	18	2.46	0.76	0.54	0.41
	Ulmus glabra	Ulmaceae	7	1	0	1.00	0.12	0.59
		total		508	39.68			

	Acer laetum	Sapindaceae	28.8	26	1.48	0.70	0.43	0.51
	Acer velutinum	Sapindaceae	34.8	24	2.39	0.74	0.54	0.44
	Carpinus betulus	Betulaceae	34.3	97	7.96	0.54	0.55	0.50
	Fraxinus excelsior	Oleaceae	63	1	0.19	1.00	1.00	0.29
	Parrotia persica	Hamamelidaceae	21.3	8	0.2	0.80	0.10	0.74
C	*Prunus avium*	Rosacea	35	3	0.18	1.00	0.67	0.60
	Quercus castaneifolia	Fagaceae	105.3	7	5.9	0.70	0.80	0.48
	Taxus baccata	Taxaceae	45.5	202	22.26	0.36	0.55	0.45
	Tilia rubra	Malvaceae	48	54	9.25	0.47	0.57	0.58
	Ulmus glabra	Ulmaceae	17.8	18	0.37	0.72	0.50	0.61
		total		440	50.19			

Each species is thus characterized by its average dbh, its contribution to total forest density, and by its immediate neighborhood. The variable mingling has a maximum value of 1.0 for *Ulmus glabra* in plots A and B. *Ulmus glabra* is only represented by one individual in these two plots, and M must therefore be 1. The mean M values for *Taxus baccata* are comparatively low (0.27, 0.33, and 0.36 in plots A, B, and C). This result is to be expected, because *Taxus baccata* occurs with a high relative frequency and is therefore likely to have more conspecific neighbors. The correlation coefficients between the six numerical variables are shown below (Table 5).

Table 5. The correlation coefficients between the six variables (mean dbh, trees per ha (N), basal area (BA), structural indices mingling (M), dominance (D), and size differentiation (T)) that were included in the analysis.

	Mean dbh	**N**	**BA**	**M**	**D**	**T**
mean dbh	1	0.02	0.22	−0.22	0.76	−0.25
N	0.02	1	0.94	−0.81	0.14	−0.15
BA	0.22	0.94	1	−0.84	0.22	−0.18
M	−0.22	−0.81	−0.84	1	−0.26	0.26
D	0.76	0.14	0.22	−0.26	1	−0.50
T	−0.25	−0.15	−0.18	0.26	−0.50	1

Our aim was to identify relationships between the relative frequency and mean size of a particular species and the structural pattern in its vicinity. The structural parameters provide additional information about the close-range neighborhood of each species. High correlation values were found between tree density and mingling for individual species, and between mean dbh and neighborhood dominance.

3.4. Relationships between Species-Specific Variables

The relationships between three variables that show high correlations were analyzed in more detail. The most important results, including the graphs and the model expressions, are shown in Figure 4. The non-linear relation between the number of trees per ha and the mean neighborhood mingling was estimated using a power function. The relation between the mean dbh (cm) and the mean neighborhood dominance is also non-linear, and was estimated using the Monod function. The relation between the mean neighborhood dominance and the mean neighborhood differentiation is linear.
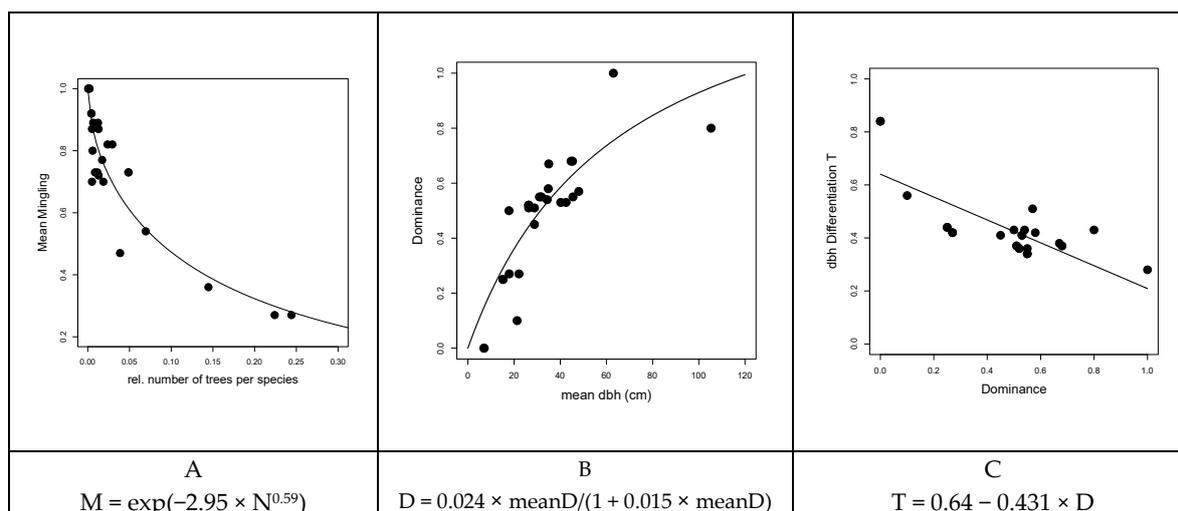
A	B	C
$M = \exp(-2.95 \times N^{0.59})$	$D = 0.024 \times \text{meanD}/(1 + 0.015 \times \text{meanD})$	$T = 0.64 - 0.431 \times D$

Figure 4. The relationships between species-specific variables in the three plots. Shown are the number of trees per ha and the mean neighborhood mingling (M) with the estimated non-linear model below (**A**); the mean dbh (cm) and the mean neighborhood dominance (D) with the estimated Monod model below (**B**); the mean neighborhood dominance and the mean neighborhood Differentiation (T) with the estimated model below (**C**).

In addition, it was found that the relation between the coefficient of variation of tree dbh's within four-tree neighborhoods (CV) and the dbh differentiation (T) is linear. This result was expected because both variables measure the degree of dbh variability. CV includes the variability of all trees in the neighborhood whereas T reflects only the average size variability between the reference tree and its neighbors. The CV values may therefore exceed the T values.

3.5. Uniform Angle Index

The average values of the uniform angle index for plots A and B in the Afratakhteh forest reserve and Siah-Roudbar forest were 0.52, 0.50, and 0.51, respectively. The three distributions of this index, shown in Figure 5, are almost identical.
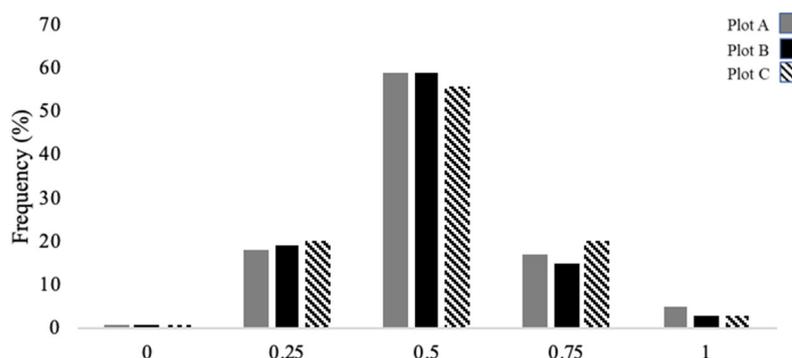
Figure 5. The very similar distributions of the uniform angle index in the three plots.

The value of the uniform angle index was found to be 0.5 in the great majority of neighborhood groups, with relative frequencies of more than 50%. Values of 0 (very regular) and 1 (very irregular) were very rare. These results reveal random spatial distributions in the three plots.

4. Discussion

In terms of evolutionary age, the Hyrcanian forests are of great importance internationally. These deciduous broadleaved forests are among the most interesting forests in the world due to the high diversity of plant species outside of the Tropics. The northern forests of Iran which have existed

for over a million years are characterized by a very particular species mix and complex structure. Sustainable management of this valuable resource depends on knowledge of the structural and ecological characteristics. Tree regeneration, growth, and mortality determine the dynamic evolution of these ecosystems [8].

Information about forest ecosystems is obtained through sampling, in field experiments, and by continuous observation. Sampling is used to assess forests, usually at regular intervals, and to prepare reports about the state of the forest resource for a given area and time. Examples are national forest inventories. Field experiments are established to test the response to particular treatments, like planting densities or fertilizer applications. The timing of field measurements is defined by the experimental protocol. Continuous observation (without manipulating the system) is essential for studying the structure and dynamics of complex ecosystems like our three *Taxus* plots. These study areas represent a considerable investment of time and money, and provide information that is essential for research and conservation.

4.1. Measuring Species Richness

The relation between plot area and species richness is non-linear. For this reason, a common standard has to be established, which allows estimation of the richness for any arbitrary plot size, and thus to make plots comparable in terms of richness. A practical way to derive such a common standard is to develop a species–area relation (SAR) for each plot individually. Richness can then be estimated for any particular area, for example, for one ha (10,000 m²). The application of this method was demonstrated in the present study.

Such results may also be obtained using an alternative approach. Preston (1962) [55], May (1975) [56], and Hubbell [57] assumed that it should be possible to estimate the minimum area that is required to capture all the species within a particular region. This assumption was considered by Gadow and Hui [58], who developed a specific relationship between the maximum number of tree species within a forest region (Smax) and the minimum area required to capture all the species within that region (Amin, measured in m²) [55–58]. That particular study was based on many tree-mapped field plots assessed in various regions of the world. The minimum species area was estimated in their study by the function $A_{min} = 487.8 \times S_{max}^{0.524}$. The result implies that, for contiguous forest areas, the form of the species-area relationship is directly defined by the maximum number of species in the region. The graphs of the species–area relations of the three plots (Figure 6, Table 2), confirm these findings.
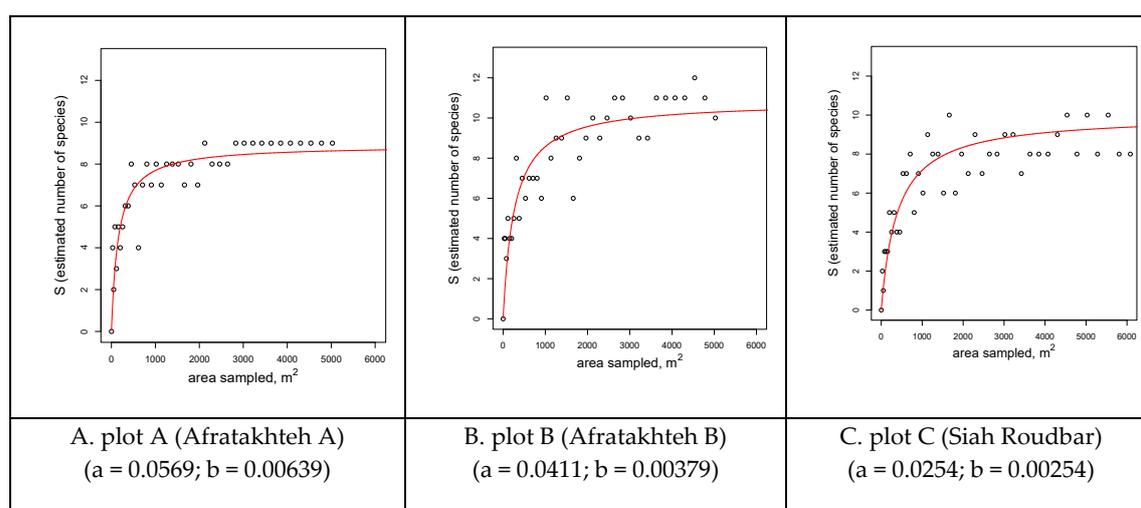

A. plot A (Afratakhteh A)	B. plot B (Afratakhteh B)	C. plot C (Siah Roudbar)
(a = 0.0569; b = 0.00639)	(a = 0.0411; b = 0.00379)	(a = 0.0254; b = 0.00254)

Figure 6. Estimated species–area relations for the three *Taxus baccata* plots (**A**, **B**, **C**); the specific parameters of the Monod model are listed between brackets (see also Table 2).

In our example, the minimum area to capture all eight species in plot A is $487.8 \times 8^{0.524} = 1450.31$ m². Inspection of the SAR of plot A in Figure 5 reveals that this result is reasonable. For plot C with 10 species, the estimated minimum contiguous area that captures all species would be 1630.2 m², again a reasonable result.

4.2. Edge-Corrected Neighborhood Groups

Reference trees that are located close to the plot edge may produce a biased estimate of the neighborhood structure. To avoid such bias, methods of edge correction have to be employed. The simplest method involves the definition of a buffer around the plot edges. Figure 7 shows two sets of reference trees with specific attributes (species and minimum size) and their neighborhoods after edge correction.
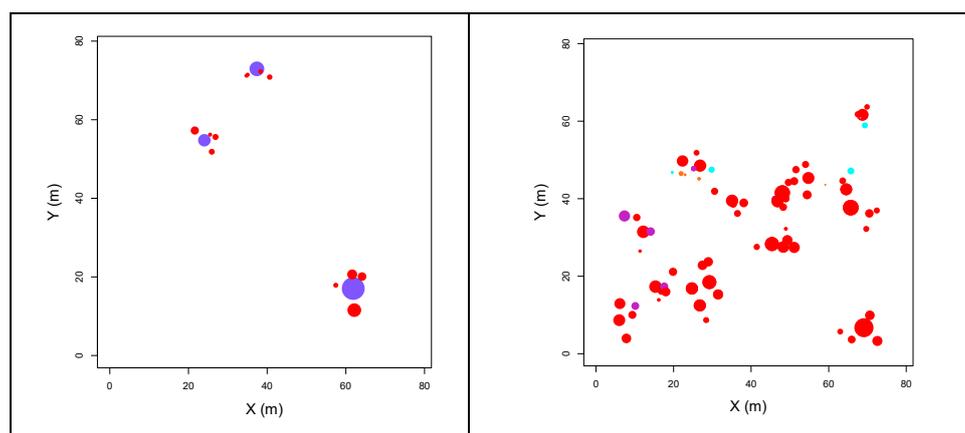

Figure 7. Two edge-corrected sets of reference and their four-tree neighborhoods in plot A (cropped to 80 × 80 m): all *Quercus castaneifolia* trees with dbh > 50 cm (left); all *Taxus baccata* trees with dbh > 50 cm (right).

The two selected reference trees and their four-tree neighborhoods are all dominant *Quercus castaneifolia* trees with a dbh > 50 and all dominant *Taxus baccata* trees, also with dbh > 50. Potential reference trees may be defined by a range of attributes, including species, tree height, or crown dimension. Instead of selecting a particular reference species, we may for example, wish to select all trees that belong to a particular family. Alternatively, all dominant trees, irrespective of the species, could be selected as reference trees to study the the neighborhoods of this particular cohort.

4.3. Measuring Tree Species Diversity

In community ecology, more attention has been paid to the measurement of species diversity than to almost any other parameter. Accordingly, there is a rich literature on diversity, with many contradictory recommendations. Most popular are Hill numbers as easily interpreted measures of diversity. This includes the exponential form of the Shannon Index (this index is sometimes called the "Shannon–Wiener" and sometimes the "Shannon–Weaver" index. The names Wiener and Weaver are similar, sometimes Wiener is spelt incorrectly as Weiner). We follow Spellerberg and Fedor [59] by referring simply to the "Shannon index" (Hill's N1) and the reciprocal of Simpson's index (Hill's N2). The choice depends on whether more weight is given to the rare species (N1) or the common species (N2). Traditional indices of biodiversity incorporate only the numbers of species and their frequencies without considering the biological differences among the species. Ganeshaiah et al. [60] proposed a measure of community diversity known as the "avalanche index" which does consider taxonomic differences (Hao et al.) [61].

The avalanche diversity does not only account for the number of species and their frequencies but also considers the taxonomic hierarchy. The Shannon entropy would be the same for two communities A and B if both have the same number of species occurring with the same frequencies. The avalanche diversity in B would exceed that in A if the number of genera would be greater in B

than in A. The reason for the difference is the fact that the avalanche index captures the intra-community biological variation. Plot A had the lowest avalanche diversity (0.24). The corresponding values for B and C are 0.31 and 0.33. Plot A has 8 species in 7 families, whereas plot C has 10 species in 9 families, which is reflected by the greater index value. The avalanche is not only useful as an index of diversity but also as a measure that can be used to assess the dissimilarity of two forest communities [61,62].

4.4. The Species Abundance Distribution

As shown in the results section, the species abundance distribution (SAD), which describes the abundances of all species recorded within the three plots combined, takes a curve shape that is defined by many rare species and a few common ones. This result confirms previous findings in communities with relatively few species [46,53]. The Monod function, which to our knowledge has never been used as a model of the species abundance distribution, shows promise as a parameter parsimonious SAD model. The overwhelming dominance of the one leading species was apparent in all three forests. A comparison of the *Taxus* study areas with plots in temperate forests in east Asia, central Europe, or species-rich tropical forests would be an interesting topic for further investigation using, for example, the methods applied by Hao et al.

4.5. The Uniform Angle Index

To quantify the positioning diversity of yew trees, the uniform angle index was used. By examining the angles between trees, the uniform angle index shows how trees are arranged relative to each other. The average value of this index for yew species in the studied plots indicates that the arrangement of yew trees is random. Kint et al. stated that the spatial pattern of populations is affected by forest management, so that in managed populations due to thinning that favors high-quality trees, the spatial distribution of trees tends to be uniform [63]. Our results show that the studied populations generally have a random arrangement, which is consistent with the research conducted by Hesabi et al. in which the univariate O-ring function was used for studying the distribution pattern of yew trees in the Afratakhteh region. The results of their study showed that the distribution pattern of adult yew trees is completely random, but the distribution pattern of their regeneration up to a 5-m distance is clumped and then random [64]. How seeds are dispersed is one of the reasons leading to the random pattern of trees (Martinez et al.). Wind and animals are the most important causes of English yew seed dispersal usually resulting in a random pattern. A study by Forget et al. in Guiana found that the dispersal of seeds by animals results in a random pattern [65]. The random spatial arrangement indicates an inter-specific competition among trees. This result is consistent with the study of Jafari Afrapoli et al. in the Afratakhteh forest reserve [66].

5. Conclusions

This study presents the biological and structural characteristics of three Hyrcanian forests dominated by *Taxus baccata* in northern Iran, based on a rare set of observations collected in three large field plots with mapped trees. The parameter-parsimonious Monod function emerged as the most appropriate model for estimating both the species–area relationship as well as the species abundance distribution. This finding could have implications for model selection in future studies. Significant correlations, and specific non-linear and linear relationships, were found between the frequency and mean size of the different species and the structural attributes in the neighborhood of individual trees. The detailed analysis contributes to raising the awareness of these unique forests and thus to effective conservation of an important natural heritage.

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