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The Relationship between Stand Structure and Tree Growth Form—Investigating the Effects of Selection Cuttings in Mountainous Mixed Beech Forests

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Abstract: Among forest management methods, selection cutting puts into practice applications that follow the processes that naturally occur in the ecosystem. The purpose of this research was to investigate the effects of selection cutting on the stand structural characteristics and growth form of trees. The effect of selection cutting was evaluated in terms of the frequency and standing volume of trees and deadwood, diversity of tree species indices, stand structural complexity index (SCI), height-to-diameter ratio (HDR) or slenderness index, and live crown ratio of trees (LCR). These were measured and estimated through a systematic random plot sampling in two adjacent parcels with different management histories (parcel A, managed using the selection cutting method, and parcel B, managed using the protected method and without cutting trees) in mixed beech forests in Northern Iran. The results showed that the standing volume, Shannon index, deadwood volume, and SCI index in parcel A were lower than in parcel B. The selection cuttings had no effect on the HDR value of the upper-storey trees, while it decreased the HDR value of the middle-storey and light-demanding trees (maple and alder) and increased the HDR value of the lower-storey and beech trees. Also, the results showed that as a result of the implementation of selection cuttings, the total LCR of the lower-storey trees increased, but the total LCR of the upper-storey trees decreased compared to the protected forest. Furthermore, the results showed that tree growth form (HDR and LCR) are related to the SCI of the stands. These results showed that the implementation of the single-selection method had simplified the structure of the stands; also, with the changes made in the growth form of trees, the possibility of snow and wind damage was increased, especially in young trees. It is necessary to prioritize the ecological values of forest deadwood, thick trees, biological diversity, and the resistance of these stands against snow and wind damage in the next cutting operations.

Keywords: selection cutting; structural complexity index; height-to-diameter ratio; live crown ratio; mixed beech stands

Citation: Karamzadeh, S.; Nikooy, M.; Abkenari, K.T.; Tavankar, F.; Lo Monaco, A.; Picchio, R. The Relationship between Stand Structure and Tree Growth Form—Investigating the Effects of Selection Cuttings in Mountainous Mixed Beech Forests. *Forests* **2023**, *14*, 1861. https://doi.org/10.3390/f14091861

Academic Editors: Xiongqing Zhang, Jinghui Meng and Henn Korjus

Received: 27 July 2023
Revised: 5 September 2023
Accepted: 8 September 2023
Published: 13 September 2023

1. Introduction

"Close to nature forestry" or "conservation forestry" requires a management approach that includes habitat expansion by increasing structural elements such as deadwood and large, old trees [1,2]. Selection cutting systems, i.e., continuous cover forestry, are intended to imitate small-scale death events by cutting individual or small groups of trees to preserve mixed species with uneven-aged stand structures [3]. This forestry method is believed to bring environmental benefits including increased carbon sequestration along with stable wood production. It is more suitable for shade-tolerant species, and it has been used in some hardwood or mixed forests. The management target of this system is to concurrently combine the objective of short-term profit and the conservation of stands with future growing stocks. The selection of trees to harvest or maintain is challenging due to the wide variety of stem qualities and defects in hardwoods in a stand [4,5]. Selection cutting involves the removal of individual trees or small groups of trees to maintain an adequate distribution of trees of different sizes. Over time, these interventions can modify stand structure in terms of attributes, such as changing composition and relative abundance of species, influencing species richness, density, and total basal area, meanwhile, the diameter distribution may change considerably due to the loss of large trees [6–17]. Basically, selection cutting can induce variations in the structure of the stand. The risk is that, if the selection management objectives are not balanced by adapting them to the forest ecosystem context, a progressive simplification of the forest stand may occur [18].

Stand structure is also described using stand attributes such as species composition, tree diameter and height, stand density and basal area, deadwood, and so on, single or associated, and their variation and heterogeneity within a stand give stand structural complexity [19].

The appearance of the growth form of a tree is the result of three main factors: (a) the hereditary characteristics of the tree itself, which inherits the genetic characteristics from the parent tree; (b) the ecological conditions that affect the growth rate and growth form of the tree; and (c) the human factor, which, through silvicultural operations and forest harvesting, determines changes in the structure of forest stands and consequently the appearance of the tree growth form. In addition, factors such as the age of the tree and its position in the forest stand play an important role in shaping and changing the growth form of trees.

Even if some authors highlighted the poor economic performance of selection cutting, there is no clear evidence in this regard, and indeed, several studies have found uneven-aged management to be fully competitive with existing even-aged management systems. As found by Kuuluvainen et al. [20], the selection cuttings maintain late-successional forest characteristics and species dynamics better than other sylvicultural treatments. As also stated by other authors [20–24], there are considerable gaps in knowledge about ecological and economic aspects. Considering these research gaps, in our opinion, the studies would need multidisciplinary research approaches with a better linkage of the research to the theory. This work was developed in order to strengthen the synergy between empirical and modelling work in the short and medium term.

Following this approach, an attempt has been made to use environmental and typical forest indices and indicators such as the stand structural complexity index (SCI), the slenderness index (HDR), and living crown length to height (live crown ratio, LCR) together with many others detailed below.

The SCI correlates the number and relative abundance of the structure attributes, functioning, and composition to delineate forest ecosystems [25]. The HDR and the LCR are two important characteristics of forest tree growth form. These characteristics of the growth form of forest trees can have a wide range of changes, which are substantially influenced by site quality (soil type, soil moisture, litter depth, slope, elevation, and exposition), stand development stage, tree density, species mixture of trees, stand structure, silvicultural treatment, logging operations, and other forest management choices. Plus, other factors that may have an effect are climatic and natural disturbances (light, wind, snow, and ice) and species provenance.

The rising global demand for wood products is a driving factor in sustainable forms of forest management, such as selective logging, which can provide revenue opportunities for developing economies [16,26]. In this sense, the study presented aims to expand the knowledge of a management system that is increasingly appreciated but of which some aspects are still insufficiently explored. The two main objectives of this research are (a) the impact assessment of selection cutting management on tree growth form (i.e., HDR and LCR) and stand structural attributes (i.e., SCI, living and dead trees, tree size distribution, and tree species diversity) as well as (b) the investigation of the relationship between stand structural attributes and growth form of trees in mountain mixed beech forests. The novelty of this study is centred on an analysis based on multi-criteria indices capable of providing a synergistic approach in evaluating the effects of a silvicultural treatment in different medium-scale time horizons. However, the research details applied to these case studies were not carried out to enucleate a concept that could be generalized to other forest realities but mainly to contribute to a scientific database for further meta-analysis and to act as guidelines for the decisions for management in the future.

2. Materials and Methods

2.1. Study Area

This research was conducted in mixed beech forests in the mountainous areas of the Hyrcanian forests in Northern Iran (Figure 1). These forests have important ecological and economic values. Hyrcanian forests have an uneven-aged mixed species structure and are managed with the selection cutting silviculture method and with a harvesting period of every 10 years.

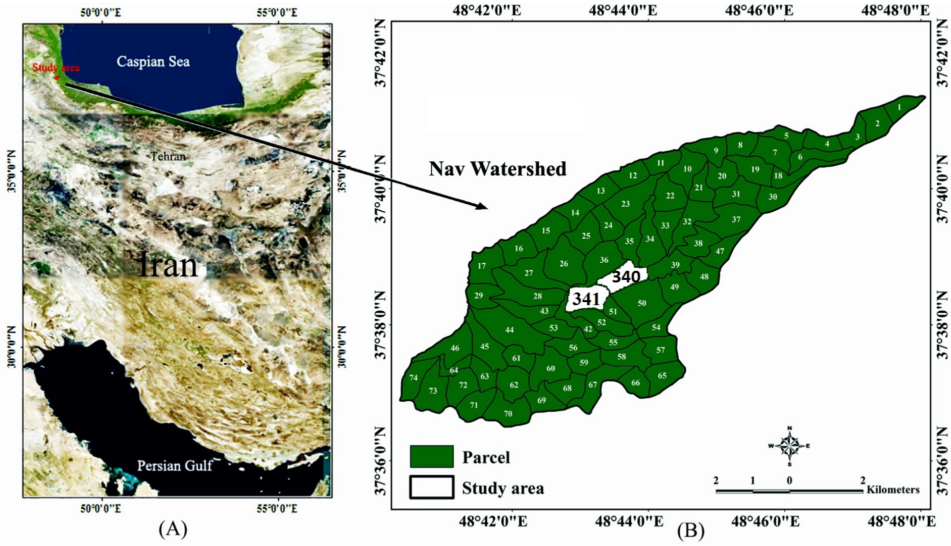

Figure 1. (**A**) Location of study area in the Hyrcanian forests; (**B**) location of studied parcels (parcel No. 340, protected management, and parcel No. 341, selection cutting management).

In order to evaluate the effects of selection cutting on the structure of the stand and the growth form of trees, two adjacent parcels with different management histories were selected in Series No. 3 in Nav Aslam Forest (Figure 1B): parcel A with an area of 56 hectares with a history of selection cutting management and parcel B with an area of 62 hectares with a management history of protection (Figure 2). These two parcels had almost similar habitat conditions and the same site index. The selection cutting parcel (A) was harvested twice in 2002 and 2012 with harvesting intensities of 32.23 and 25.95 m^3/ha, respectively (Table 1). The harvesting operations were performed with a semi-mechanized method using a chainsaw and wheeled skidder. However, timber harvesting has not been performed in the protected parcel (B) since the preparation and implementation of the forest management plan (1975) until now. The altitude in these parcels is from 1200 to 1350 m, the average annual temperature is 10.2 °C, and the average annual rainfall is 1100 mm. The forest soil is deep with proper drainage and is of the forest brown type.

2.2. Data Collection

Data collection was conducted in the summer of 2022. The systematic plot sampling method was used to estimate the volume of living trees and snags. The grid was positioned in the north-south direction with a random starting point. The dimensions of the network were 100 m by 100 m, the shape of the plots was circular (radius = 17.85 m), and the area of each plot was 1000 m^2. The intersection of the grid dimensions was considered the centre of each plot. In total, 55 plots were placed in the selectively logged parcel (9.82% of the parcel area), and 60 plots were placed in the protected parcel (9.68% of the parcel area). The diameter at breast height (H = 1.3 m, DBH) and the height of all living trees and snags (DBH $\geq$ 7.5 cm) were measured in each plot. The DBH of trees and snags was measured using a forest calliper ($\pm$0.1 cm accuracy), and the height was assessed with a clinometer ($\pm$0.1 m). With these parameters, via a local tree volume table of two factors (DBH and tree height), the stem volume of living trees and snags with a height of more than 4 m was estimated. The crown length was measured using a hypsometer in m, and the crown diameter was measured using a tape on the ground in cm. The volume of fallen boles and snags with a height of less than 4 m (short snag) was calculated using Huber's formula ($V = (dm^2/4) \times \pi \times L$), where V is volume (m^3), dm is diameter under the bark at the middle of a short snag or fallen bole (m), and L is the height of a short snag or fallen bole (m).

(**a**) (**b**)

Figure 2. The mixed beech stands of study area. A view of selection cutting parcel (**a**) and of protected parcel (**b**).

Table 1. Stand and harvesting volume of selection cutting and protected parcels in previous logging periods.

Year of Operation		Parcel A (Selection Cutting)		Parcel B (Protected)
		Standing Volume (m^3/ha)	Harvested Volume (m^3/ha)	Standing Volume (m^3/ha)
2002	Before cutting	395.04	32.23	399.68
	After cutting	362.81		
2012	Before cutting	434.05	25.95	442.03
	After cutting	408.10		

2.3. Analysis of Data

2.3.1. Height-to-Diameter Ratio (HDR)

HDR is a tree-level slenderness index used to analyse tree and stand stability. High values of HDR suggest that trees have grown in a dense stand with mutual support from adjacent trees. Lower values of HDR denote longer crown length, higher crown projection area, better-developed root system, lower position of the centre of gravity, and higher stability of the trees. Therefore, trees with higher HDR values (slender trees) are much more prone to wind damage. The effectiveness and efficiency of thinning can also be assessed by estimating HDR variations. HDR is applied to assess the vigour and health of trees, as well as being a prominent predictor to describe competition effects in various forest models. The height-to-diameter ratio (HDR), alternatively referred to as the slenderness index, was computed as the ratio of total tree height to diameter at breast height for each tree.

The height-to-diameter ratio of trees was obtained using Equation (1) [27]:

$$\mathrm{HDR} = \frac{\mathrm{H_{tot}}}{\mathrm{DBH}} \quad (1)$$

The HDR is the slenderness index (or height-to-diameter ratio), H_{tot} is the total tree height (cm), and DBH is the diameter at breast height (cm). Both H_{tot} and DBH are expressed in the same units, therefore HDR is dimensionless. The HDR value of the trees was calculated separately for the lower-storey trees (tree height < 15 m), middle-storey trees (tree height 15–22.5 m), and upper-storey trees (tree height > 22.5 m).

2.3.2. Live Crown Ratio (LCR)

The LCR is a descriptor of the size of the tree crown and thus provides information on photosynthetic capacity, and thus stem diameter and growth vitality, and indirectly on stability in relation to stand density and the level of the neighbouring competition [28].

In the current literature, a live crown ratio (LCR) of about 30%–40% is indicated for strong growth, particularly in diameter. Therefore, trees with a long crown are considered to have a tapered stem (low HDR), while those with a limited crown length have a thin stem (high HDR) and are consequently more vulnerable [28].

The live crown ratio (LCR) was computed as the ratio between the length of the living crown and the total height of the tree, both in metres. The live crown ratio of trees was obtained using Equation (2) [27]:

$$\mathrm{LCR} = \frac{\mathrm{CL}}{\mathrm{H_{tot}}} \tag{2}$$

The LCR is live crown ratio, CL is crown length (m), and H_{tot} is total tree height (m). Both H_{tot} and CL are expressed in the same units, therefore LCR is dimensionless. The LCR value of the trees was calculated separately for the lower-storey trees (tree height < 15 m), middle-storey trees (tree height 15–22.5 m), and upper-storey trees (tree height > 22.5 m).

2.3.3. Relative Spacing Index (RSI)

The RSI is assumed as a more effective density measure than others because it incorporates the number of stems per hectare, site quality, and stand development through the dominant height (HDOM) of trees [29]. The HDOM has been frequently used to describe the combined effect of site quality and stand development stage in modelling various tree characteristics [29]. The HDOM was estimated by averaging the measured heights of the largest trees in each sample plot regardless of tree species [30]. The RSI was obtained using Equation (3) [29,31,32]:

$$\mathrm{RSI} = \frac{\sqrt{\frac{10{,}000}{\mathrm{N}}}}{\mathrm{HDOM}} \tag{3}$$

where N is tree density (stem/ha) and HDOM is the dominant height of trees (m).

2.3.4. Tree Diameter Diversity Index

The Shannon index is a widely used measure of tree size complexity for diameter distributions, which allows a direct comparison of different distributions through one single value. The tree diameter diversity was obtained using Equation (4) [25,33,34]:

$$\mathrm{TDD} = -\sum_{i=1}^{n} p_i \ln p_i \tag{4}$$

where n is the number of diameter classes and p_i is the proportion of an individual tree in the ith diameter class.

2.3.5. Tree Height Diversity Index

The tree height diversity was obtained using Equation (5) [25,33,34]:

$$\mathrm{THD} = -\sum_{i=1}^{n} p_i \ln p_i \tag{5}$$

where n is the number of height classes and P_i is the proportion of an individual tree in the ith height class.

2.3.6. Canopy Tree Species Richness Index

Due to the fact that the forests of the study area had an uneven-aged and mixed-species structure, it was possible that the species richness of the whole trees was different from the species richness of the canopy layer (dominant) trees. Therefore, in this research, tree species richness was calculated both for all trees (all diameters and heights) and for the dominant trees. The canopy tree species richness was obtained using Equation (6) [34,35]:

$$TSR_c = -\sum_{i=1}^{n} p_i \ln p_i \quad (6)$$

where n is the number of species in the canopy layer and P_i is the proportion of basal area of the *i*th species.

2.3.7. Stand Structural Complexity Index

The structural complexity index of the stand was obtained using Equation (7) [25,36]:

$$SCI = \frac{TDD + THD + TSR_c}{n} \quad (7)$$

The SCI is the stand structural complexity index, TDD is tree diameter (size) diversity, TDH is tree height diversity, TSR_c is tree species richness in the canopy layer, and n refers to the number of structural attributes used in the index (n = 3). The index equates the increased structural complexity (higher index values) with increasing tree diameter and height variation as well as canopy tree species richness.

2.3.8. Tree Species Diversity Index (TSD)

The Shannon–Weiner diversity index is a common and robust method for calculating the level of biodiversity. The Shannon–Wiener index applies an information–theoretic approach to predict which species the next collected plant individual belongs to, and if the community species diversity is higher, the greater the uncertainty is in predicting the next individual [37]. It was obtained using Equation (8) [34]:

$$TSD = -\sum_{i=1}^{s} p_i \ln p_i \quad (8)$$

where TSD is the tree species diversity index according to Shannon–Wiener index (H') and P_i is the ratio of the number of the *i*th species to the overall number of species.

2.3.9. Tree Species Evenness Index (TSE)

The Pielou evenness index reflects the distribution of the individuals of all species in a community, and the higher the species evenness index, the more evenly the number of individuals of each species is distributed [37]. It was obtained using Equation (9) [38]:

$$TSE = -\sum_{i=1}^{s} \frac{p_i \ln p_i}{\ln S} \quad (9)$$

where TSE is the tree species evenness index according to Pielou's evenness index (J_{sw}), p_i is the ratio of the number of the ith species to the overall number of species, and S is the number of species.

2.3.10. Tree Species Richness Index (TSR)

The Margalef richness index is an index reflecting the number of species in a community. It was obtained using Equation (10) [39]:

$$TSR = \frac{S - 1}{\ln N} \tag{10}$$

where TSR is the tree species richness index according to the Margalef richness index, S is the number of species, and N is the total number of individuals of all species.

2.3.11. Species Importance Value (SIV)

Species importance value (SIV) was determined to analyse the species composition and species domination. The SIV for each tree species was calculated using Equation (11):

$$SIV = RD + RF + RD_o \tag{11}$$

where RD is relative density, RF is relative frequency, and RD_o is relative dominance. Relative frequency (RF) is calculated as follows: RF = (number of sample plots containing a species × 100)/total number of sample plots. Relative density (RD) is calculated as follows: RD = (number of individuals of a species × 100)/total number of individuals of all species. The basal area of tree species was considered for dominancy, and the relative dominance (RD_o) is calculated as follows: RD_o = (basal area of a species × 100)/total basal area of all species.

2.3.12. Species Composition of Trees

The ratio of the number of individuals of each species to the number of individuals of all species in each sample plot (relative density of each tree species) was calculated, and species with a relative density equal to or greater than 5% were included in the composition of tree species.

2.4. Statistical Analysis

Data analysis was conducted using SPSS statistical software version 20.0 (IBM Crop, Armonk, NY, USA). In order to compare stand structural indices (SCI) and tree growth form indices (HDR and LCR) in two parcels (selection cutting and protected), the mean indices were compared through an independent samples *t*-test. Before performing these tests, the normality of the data distribution was checked and confirmed ($\alpha = 0.05$) through the Kolmogorov–Smirnov test, and the equality of variances was checked through the Levene's test. The correlation between tree growth form indices and stand structural indices was investigated through the Pearson correlation test.

3. Results

3.1. Stand Characteristics

The number of beeches in the selection cutting parcel (55.9%) was significantly lower than that of the protected parcel (62.3%), but the share of maple (17.4%) and alder (9.5%) in the selection cutting parcel was significantly higher than that of the protected parcel (10.1% and 5.0%, respectively) (Table 2). There was no significant difference in the number of hornbeam trees in the two parcels, but the share of other species in the selection cutting parcel (3.6%) was significantly lower than that of the control parcel (7.9%).

The density of living trees, dead trees, the volume of dead trees and fallen boles, the basal area, and the standing volume of living trees in the selection cutting parcel were lower than those in the protected parcel.

The average DBH of living trees and dead trees in parcel A was significantly lower than that in parcel B. The average height of living trees was not significantly different in the two parcels, but the average height of dominant trees in parcel A was significantly lower than that in parcel B. The average DBH of dead trees in parcel A was significantly lower than that in parcel B.

Table 2. Stand structural attributes in parcel A (selection cutting) and parcel B (protected). Be: Beech (*Fagus orientalis* Lipsky), H: Hornbeam (*Carpinus betulus* L.), M: Maple (*Acer velutinum* Boiss), Al: Alder (*Alnus subcordata* C.A.M.), and other species (*Ulmus glabra* Huds., *Acer cappadocicum* Gled., *Tilia begonifolia* Stev., *Fraxinus coriarifolia* Scheel, and *Quercus castaneifolia* C.A.M.).

Stand Structural Attributes	Parcel A	Parcel B
Species composition of trees (% of number)	Be (55.9%) *, H (16.3%) N.S., M (17.4%) *, Al (9.5%) *, Other Sp. (3.6%) *	Be (62.3%), H (14.7%), M (10.1%), Al (5.0%), Other Sp. (7.9%)
Crown closure (%)	84.7 ± 5.2 N.S.	88.5 ± 4.9
Species number of canopy layer	3.7 ± 0.9 **	4.6 ± 1.1
Density of living trees (stem ha^{-1})	323.5 ± 16.0 **	397.4 ± 32.5
Average DBH of living trees (cm)	27.5 ± 16.2 **	33.5 ± 16.8
Average height of living trees (m)	21.2 ± 2.4 N.S.	23.7 ± 2.6
Average height of dominant trees (m)	26.4 ± 2.3 **	29.5 ± 2.1
Density of dead trees (stem ha^{-1})	10.1 ± 2.0 **	18.9 ± 1.7
Average DBH of dead trees (cm)	31.1 ± 5.1 **	43.0 ± 5.2
Average height of dead trees (m)	16.7 ± 1.9 **	23.6 ± 2.4
Volume of dead trees (m^3 ha^{-1})	8.3 ± 109 **	15.7 ± 1.8
Volume of fallen boles (m^3 ha^{-1})	8.4 ± 1.5 **	11.8 ± 1.7
Basal area of living trees (m^2 ha^{-1})	24.5 ± 2.2 **	29.8 ± 2.5
Standing volume of living trees (m^3 ha^{-1})	443.4 ± 15.3 *	486.4 ± 20.6

Note: N.S. indicates no significant differences; * indicates significant differences at α = 0.05; and ** indicates significant differences at α = 0.01.

The average species number of the canopy layer in the selection cutting parcel (3.7 species) was significantly lower than that in the protected parcel (4.6 species).

The relationship analysis between the density and DBH of trees showed that the tree density decreased with the increasing DBH of trees in both parcels (Figure 2).

There was a significant relationship ($p < 0.01$) between the density of trees and DBH classes (R^2 = 0.73 and R^2 = 0.89 for parcel A and parcel B, respectively), and the shape of the curve in both parcels was an inverted J-shape (Figure 3). The density of trees with a DBH of less than 40 cm in parcel B was lower than that in parcel A, but the density of trees with a DBH greater than 40 cm in parcel A was lower than that in parcel B.

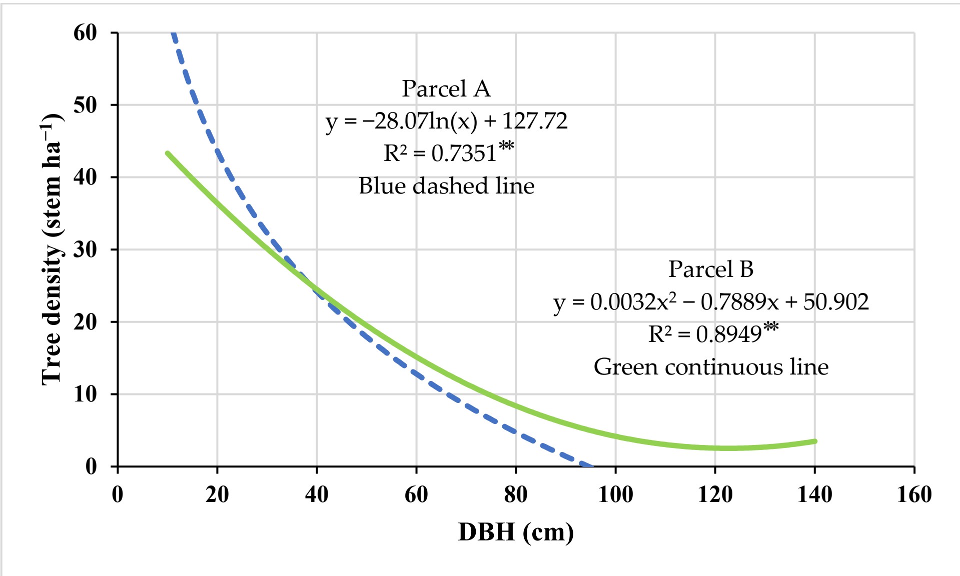

Figure 3. Tree density in DBH classes in the studied parcels. ** indicates a $p < 0.01$.

The tree height–DBH curves and regression analysis (Figure 4) indicated that there was a significant relationship ($p < 0.01$) between tree height and DBH. The height of trees increased with the increasing DBH of trees. In the same diameters, up to a DBH of about 80 cm, the height of the trees in parcel A was higher than that in parcel B. The height difference was greater in the small diameter classes; however, as trees' DBH increased, the height difference between the two parcels decreased.

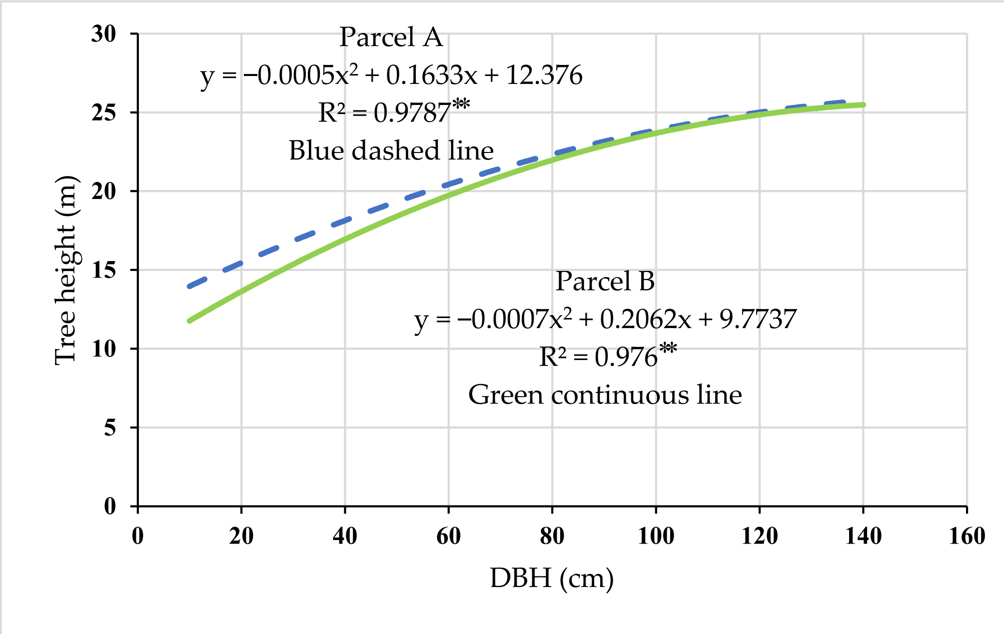

Figure 4. Tree height in DBH classes in the studied parcels (parcel A: selection cutting and parcel B: protected). ** indicates a $p < 0.01$.

The density of beech and hornbeam in parcel A was significantly lower than that in parcel B (Figure 5A). The frequency of other tree species in parcel A was also significantly lower than that in parcel B. However, the density of maple and alder trees showed no significant differences between the two parcels. The basal areas of beech were not significantly different in parcel A and parcel B, while the basal areas of hornbeam, maple, and other tree species in parcel A were significantly lower than those in parcel B (Figure 5B). The standing volume values of beech and hornbeam in parcel A were significantly lower than in parcel B (Figure 5C). The standing volume values of maple and alder trees were not significantly different in the two parcels. The standing volume of other tree species in parcel A was significantly lower than that in parcel B.

3.2. Stand Structural Indices

The results indicated that the density of middle- and upper-storey trees in parcel B was significantly higher than that of parcel A, while the density of lower-storey trees was not significantly different in the two parcels (Table 3).

The results showed that the HDR value of lower-storey trees in parcel A was significantly higher than that of parcel B, while the HDR value of middle-storey trees in parcel A was significantly lower than that of parcel B, and the HDR values of upper-storey trees in the two parcels were not significantly different from each other (Table 3).

The LCR value of lower-storey trees in parcel A was significantly higher than that of parcel B, while the LCR value of upper-storey trees in parcel A was significantly lower than that of parcel B, and the LCR values of middle-storey trees in the two parcels were not significantly different from each other.

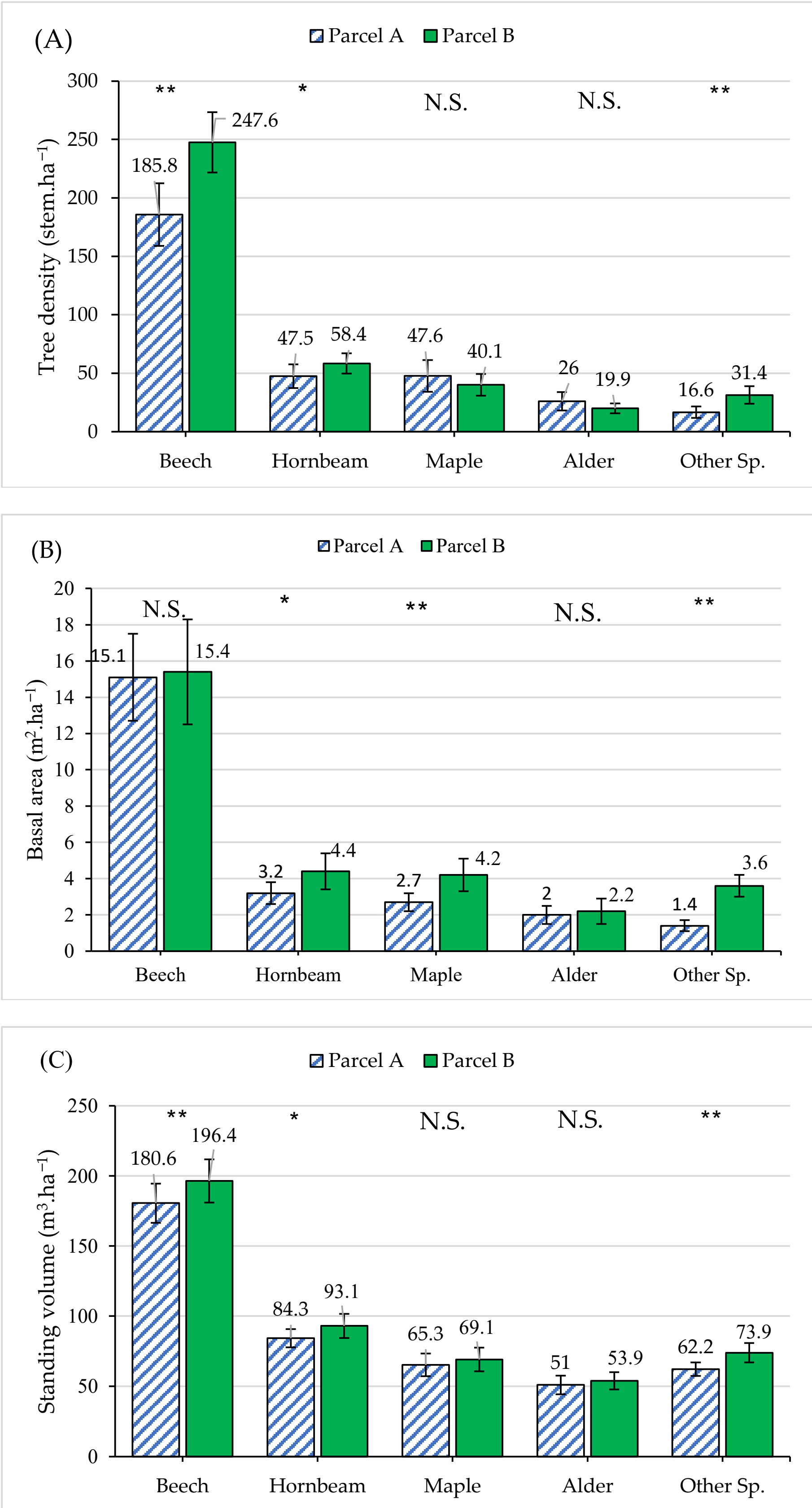

Figure 5. Tree density (**A**), basal area (**B**), and standing volume (**C**) of tree species in selection cutting (parcel A) and protected (parcel B) parcels. N.S. indicates no significant differences; * indicates significant differences at $\alpha = 0.05$; and ** indicates significant differences at $\alpha = 0.01$.

Table 3. Density, HDR, and LCR values in the studied parcels (A: selection cutting and B: protected) according to tree storey layers.

Tree Storey (Tree Height, m)	Density (Stem ha^{-1})		HDR		LCR	
	Parcel A	Parcel B	Parcel A	Parcel B	Parcel A	Parcel B
Lower (<15, m)	183.5 ± 20.2 N.S.	181.5 ± 14.0	119.0 ± 11.5 **	94.8 ± 8.1	0.27 ± 0.03 *	0.22 ± 0.03
Middle (15–22.5, m)	112.2 ± 20.2 **	170.6 ± 15.3	70.3 ± 5.3 *	88.6 ± 7.4	0.28 ± 0.03 N.S.	0.29 ± 0.04
Upper (>22.5 m)	27.8 ± 4.0 **	45.3 ± 4.5	51.9 ± 3.6 N.S.	50.2 ± 3.5	0.33 ± 0.04 *	0.37 ± 0.04

N.S. indicates no significant differences; * indicates significant differences at α = 0.05; and ** indicates significant differences at α = 0.01.

The results showed that the HDR value of beech trees in parcel A was significantly higher than that of parcel B, while the HDR value of maple and alder trees in parcel A was significantly lower than that of parcel B. There was no significant difference between the two parcels (Figure 6).

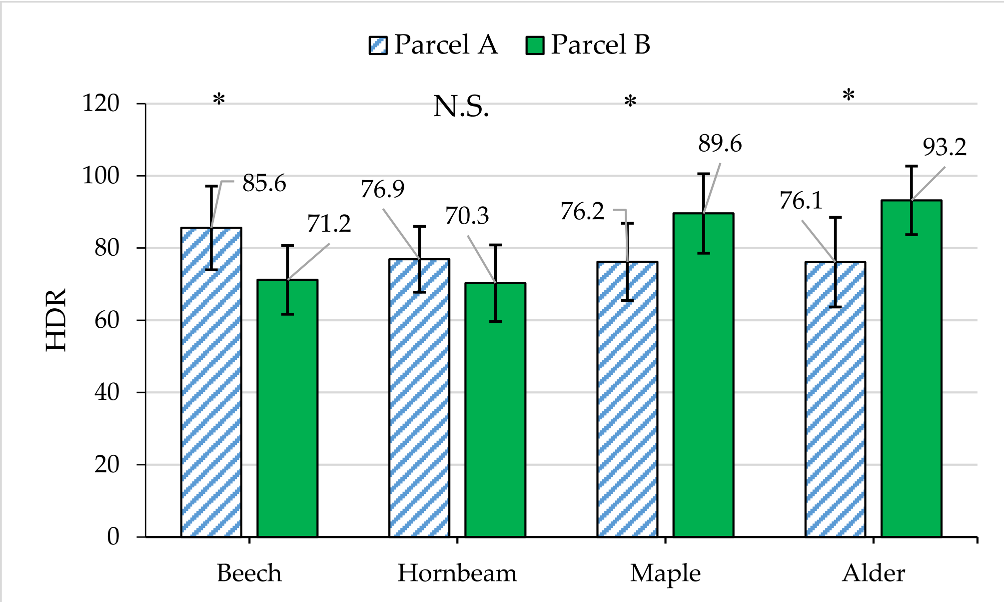

Figure 6. The height-to-diameter ratio (HDR) in tree species in the studied parcels (parcel A: selection cutting and parcel B: protected). N.S. indicates no significant differences; * indicates significant differences at α = 0.05.

The LCR value of beech trees in parcel A was significantly lower than its value in parcel B, while the LCR value of maple and alder trees in parcel A was significantly higher than their values in parcel B. LCR of the hornbeam trees was not significantly different in the two parcels (Figure 7).

In Table 4, the examined stand structural indices were reported. The results indicated that the average RSI value in parcel A was significantly higher than that in parcel B. The average values of the three indices of tree species diversity (richness, evenness, and diversity) in parcel A were significantly lower than their values in parcel B (Table 4), as well as the average species richness of the canopy layer (TSR_c), tree diameter diversity, tree height diversity, and tree species richness in the canopy layer.

The average SCI in parcel A (0.89) was significantly lower than that of parcel B (1.30) (Table 4), while the SIV of beech and alder trees in parcel A was significantly higher than their respective SIV in parcel B, and the SIV of hornbeam, maple, and other tree species in parcel A was lower than their respective SIV in parcel B (Figure 8).

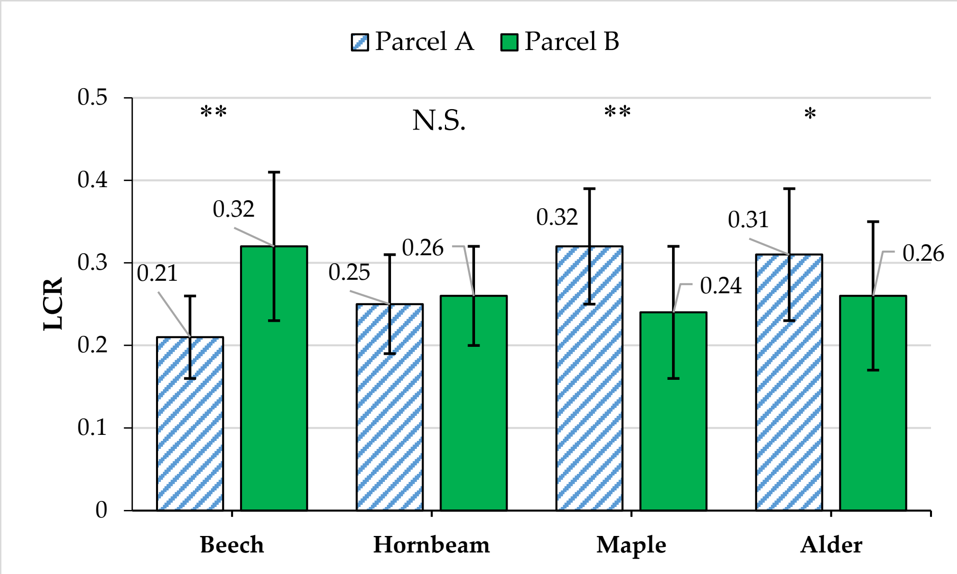

Figure 7. The live crown ratio (LCR) in tree species in the studied parcels. N.S. indicates no significant differences; * indicates significant differences at α = 0.05; and ** indicates significant differences at α = 0.01.

Table 4. Stand structural indices in parcel A (selection cutting) and parcel B (protected).

Stand Structural Attributes	Parcel A	Parcel B
Relative spacing index (RSI)	0.21 ± 0.05 *	0.17 ± 0.03
Stand structural complexity index (SCI)	0.89 ± 0.09 **	1.30 ± 0.10
Tree diameter diversity (TDD)	1.16 ± 0.20 **	1.81 ± 0.34
Tree height diversity (THD)	0.95 ± 0.11 *	1.28 ± 0.12
Canopy tree species richness (TSRc)	0.52 ± 0.10 *	0.72 ± 0.10
Tree species diversity (TSD)	1.43 ± 0.11 *	1.56 ± 0.11
Tree species evenness (TSE)	0.71 ± 0.08 *	0.88 ± 0.06
Tree species richness (TSR)	1.25 ± 0.07 **	1.76 ± 0.08

Note: * indicates significant differences at α = 0.05; ** indicates significant differences at α = 0.01.

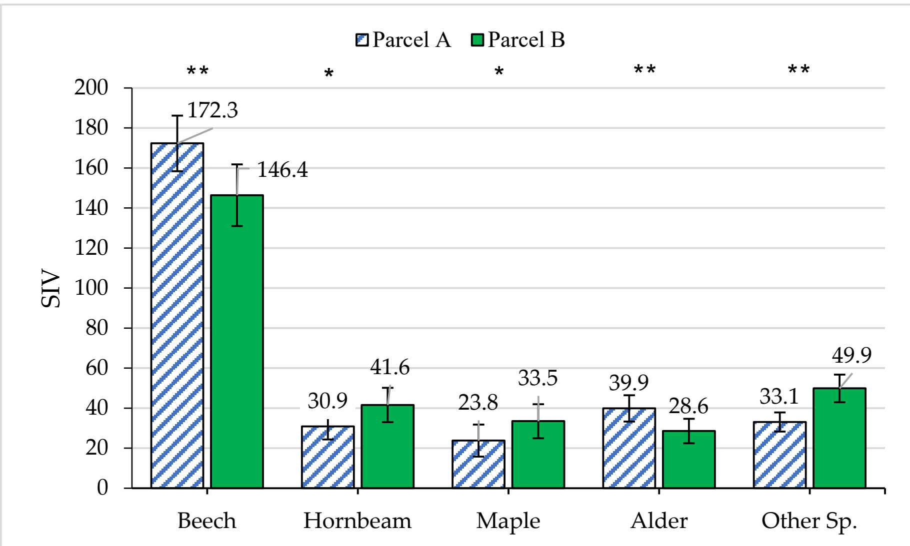

Figure 8. Species importance value (SIV) of tree species in selection cutting (parcel A) and protected (parcel B) parcels. * indicates significant differences at α = 0.05; ** indicates significant differences at α = 0.01.

The Pearson's correlation analysis between stand attributes and the growth form of trees is reported in Table 5. It is worth noting that a positive significant correlation was found between HDR and LCR for SVT, THD, TSRc, and SCI. Moreover, HDR showed a positive significant correlation with CCT, DLT, BAT, and TDD, while LCR showed a negative correlation with CCT and DLT. As expected, a significant negative correlation between HDR and LCR was found.

Table 5. Pearson's correlation coefficient (r value) between stand attributes and growth form of trees (CCT: crown closure of trees; DLT: density of living trees; DDT: density of dead trees; VDT: volume of dead trees; CWD: volume of coarse woody debris; BAT: basal area of living trees; SVT: standing volume of living trees; TDD: tree diameter diversity; THD: tree height diversity; TSRc: tree species richness of canopy layer; SCI: stand structural complexity index; TSE: tree species evenness index; TSD: tree species diversity index; HDR: height-to-diameter ratio of trees; and LCR: live crown ratio of trees).

	CCT	DLT	DDT	VDT	CWD	BAT	SVT	TDD	THD	TSR_c	SCI	TSE	TSD	HDR	LCR
CCT	1.00														
DLT	0.65 **	1.00													
DDT	0.34 *	0.36 *	1.00												
VDT	0.36 *	0.40 *	0.78 **	1.00											
CWD	−0.33 *	0.47 **	0.51 **	0.55 **	1.00										
BAT	0.17	0.20	0.06	0.09	0.10	1.00									
SVT	0.18	0.16	0.13	0.36 *	0.35 *	0.76 **	1.00								
TDD	−0.37 *	−0.34 *	0.08	0.14	0.34 *	0.35 *	0.37 *	1.00							
THD	−0.37 *	−0.39 *	0.08	0.10	0.38 *	0.40 *	0.47 *	0.73 **	1.00						
TSR_c	0.59 **	0.46 *	0.13	0.45 *	0.43 *	0.48 *	0.51 **	0.53 **	0.62 **	1.00					
SCI	0.47 **	0.69 **	0.15	0.44 *	0.41 *	0.53 **	0.55 **	0.83 **	0.65 **	0.79 **	1.00				
TSE	0.44 *	0.36 *	0.03	0.03	0.04	−0.09	−0.07	−0.08	0.11	−0.04	−0.08	1.00			
TSD	0.14	0.30 *	0.19	0.31 *	0.44 *	0.43 *	0.36 *	0.39 *	0.39 *	0.52 *	0.65 **	0.70 **	1.00		
HDR	0.76 **	0.69 *	−0.03	−0.06	−0.02	0.43 *	0.55 *	0.35 *	0.51 *	0.46 *	0.40 *	0.10	0.26	1.00	
LCR	−0.49 *	−0.63 *	0.09	0.05	0.06	0.19	0.37 *	0.10	0.44 *	0.38 *	0.42 *	0.08	0.11	−0.68 **	1.00

Note: * indicates significant differences at $\alpha = 0.05$; ** indicates significant differences at $\alpha = 0.01$.

4. Discussion

In this research, the effect of selection cutting management on the stand structure and HDR and LCR of trees in the mixed beech forests of Northern Iran was investigated. For this purpose, the structural attributes of the stand and the growth forms of trees in a selectively managed parcel (A) and a protected parcel (B) were compared.

4.1. Stand Structure

The composition of tree species in the two parcels was different, so that the abundance of beech trees in the selection cutting managed parcel (A) was lower than that of the protected parcel (B). The abundance of light-demanding species, such as alder and maple, was higher than that of the protected stand. Such results are similar to the findings observed in recent investigations [40]. The reason for this is probably due to the selection cuttings, which allow for more light and thus improve conditions for the establishment and growth of seedlings of light-demanding species such as maple and alder as compared to less light-tolerant species such as beech. Only the crown closure value showed no significant differences, which is not surprising given the forest management regime and the fact that the last intervention dates back to about ten years ago, with a harvesting intensity of about 26 m^3/ha.

The height of the trees in parcel A was higher than that in parcel B. The height difference was greater in the small diameter classes; however, as trees' DBH increased, the height difference between the two parcels decreased. One possible reason here is that the selection cutting could release space and give more light to the understory trees. Thus, for the small-diameter trees their heights are higher in Parcel A than those in Parcel B.

The density, basal area, and standing volume of trees in the managed parcel were lower than those in the protected parcel. The research results of Sefidi and Etemad [41] also indicated that the density and standing volume of trees in selectively managed forests were lower than those of protected forests or virgin forests. The density of middle- and upper-storey trees determined the difference between parcels A and B when the density of lower-storey trees was not significantly different in the two parcels. Also, the density and volume of dead wood (snags and fallen boles) in the managed parcel was lower than that of the protected parcel. In the managed parcel, the volume of snags was about 47%, and the volume of fallen boles was about 29%, lower than that of the protected parcel. Tavankar et al. [40] reported that single-selection management reduced the volume of dead wood. Usually, in single-selection management, large and thick trees are selected and cut, and these can no longer become snags or tree microhabitats [42,43]. Deadwood in forests is recognized as having a great ecological role as an engine of biodiversity [44–46], favouring the presence of plants, including tree seedlings [47–49], animals, and microorganisms that exploit the different categories and phases of decomposition [44,50] for trophic purposes, shelter, and nesting [51–56]. It also performs the function of regulating hydrological processes as well as having a significant role in the cycling of nutrients and carbon [57–60]. Ranius et al. [61] demonstrated that managing forests according to the Forest Certification Standard, the amount of deadwood with a diameter larger than 10 cm would be almost three times higher than the amount in today's managed forests. A greater awareness of the dynamics of deadwood is essential in the management of these mixed forests. In addition to producing high-quality timber, it is important to carefully observe the dynamic indicators of deadwood during the management.

The results demonstrated that the average number of the canopy layer species in the managed parcel was lower than that in the protected parcel by about 20%. In addition, both the tree diameter and the tree height diversity index in the managed parcel (A) were lower than those in the protected parcel (B). The reason for the decrease in the number of canopy layer species, the tree diameter, and the tree height diversity indices can be again attributable to the cutting of tall and thick trees in the managed parcel. A confirmation of this evidence is provided by the DBH classes above 100 cm found only in the protected parcel. In the research carried out in the Bornean rain forests, a decrease in the abundance of thick trees in single-selection stands has been reported [62]. The lower value of these indices together with the lower tree species richness index of the canopy layer in the managed parcel compared to the protected parcel caused a decrease in the stand structural complexity index (SCI). A direct indicator of potential biodiversity is structural diversity because the diversification of the stand structure provides suitable habitats for forest-dwelling organisms. Qiu et al. [63], in evergreen broadleaf forests, found that selection cutting of low and medium intensities caused little variation in the stand structure, while high-intensity selection cutting induced significant changes in the stand structure.

Both stands had, as expected, an uneven-aged structure. Importantly, the difference in the frequency of large trees was lower in the managed plot (A) than in the protected plot (B). Similar results were found in the same watershed, in a study comparing the shelterwood system, the selection cutting system, and a protected area since the 1970s [40], indicating that the tree frequency was significantly lower in managed stands than in protected stands, especially the frequency of large diameter trees.

The density of beech and hornbeam trees in the managed parcel was lower than that in the protected parcel. On the contrary, the density of maple, alder, and other species was higher in the managed parcel than that in the protected parcel. The results show that the selection cutting promotes the regeneration and growth of sun-tolerant and pioneer tree species. These results are confirmed by the fact that the tree species diversity indices in the managed parcel are lower than those in the protected parcel. Although the frequency, basal area, and volume of beech in the managed parcel were lower than those in the protected parcel, the SIV was higher in the managed parcel than that in the protected parcel, indicating that single-selection cutting increased the relative density, frequency, and dominance of this species compared to other tree species. Some authors [64] consider selection cutting among the low-impact systems and report that it does not alter species richness. However, our results indicate that, approximately 10 years after the last forestry intervention, an influence related to cutting was demonstrated. Forest management leads to changes in the horizontal and vertical structures, refs. [65,66] and in species composition [67,68]. Awareness of the impact of forest management practices on plant species diversity is important for ecologically sustainable forest management [69–71]. It is a well-established consensus in forest ecology that management choices are a major determinant of forest diversity and that a more complex forest structure is attributable to a high diversity of plant and animal species [72–74]. Certain silvicultural practices can recover biological diversity in managed forests, such as retaining old trees [75], maintaining adequate levels of deadwood [76], creating mixed stands [77] or extending the rotation period [78]. Loss in structural diversity, a tendency common in actively managed forests, impairs the capability of forests to conserve biological diversity, which may have a negative effect on ecosystem resilience, especially in the context of climate change [79].

4.2. HDR and LCR of Trees

In this research, HDR and LCR indices were used to evaluate the effects of selection cuttings on the tree growth form. HDR and LCR have been proven to be important tree-level attributes for predicting which are cull trees [80] and which are of a certain stem quality class [81].

The results showed that cuts had no effect on the HDR value of the upper-storey trees, while they decreased the HDR value of the middle-storey trees and increased the HDR value of the lower-storey trees. These results seem logical because by making cuts and with enough light reaching the middle-storey trees, the competition for light is reduced, and these trees focus on DBH growth. Regarding the trees of the lower storey, there is also a rapid increase in the height of light-demanding trees.

The results demonstrated that the HDR value of beech trees in the managed parcel was higher than that in the protected parcel, while the HDR values of maple and alder trees in the managed parcel were lower than that in the protected parcel.

The HDR value of trees is an important stand structural index in effective silvicultural tending and forest management, also indicating a stability measure of tree and stand [29]. By assessing the extent to which trees and stands are more susceptible to snow, ice, and wind damages, forest managers can better plan silviculture prescriptions based on the range of HDR [82–84].

The HDR index of forest trees varies depending on the condition of the structure and density of forest trees. Thus, in dense forest stands where the trees are taller and have a smaller DBH, the HDR index is usually higher. On the contrary, in less dense stands where the trees are placed at a greater distance from each other, the stems have a lower height and a larger diameter, therefore the HDR index is lower. It seems that the cuts made have provided better conditions, reducing light competition and increasing the diameter growth for light-demanding tree species in the studied forests (maple and alder), and have reduced their HDR value compared to the protected parcel. Rudnicki et al. [85] in their study of a pine stand in Alberta, Canada, concluded that the HDR index has a direct relationship with the degree of crown closure, in closed stands due to high growth in height and low growth in diameter, and the amount of stability against windfall is lower. Tavankar et al. [54] investigated the damage of heavy snowfall on trees in mountain-mixed beech forests in Northern Iran. Their results showed that the average HDR of damaged trees (0.70) was higher than the value of HDR of undamaged trees (0.58). The highest value of HDR (0.77) was observed in bent trees. They noted that as tree HDR increased, the frequency of snow damage increased.

Liu et al. [86] found that thinning operations caused an increase in diameter and a decrease in the HDR index of trees in the managed stand compared to the control stand. The mechanical properties of the stem may be evaluated using HDR; for example, trees with a small HDR can have a higher bending movement than trees with a larger HDR of similar heights [87,88].

The results showed that as a result of the implementation of selection cuttings, the LCR value of the lower-storey trees increased, but the LCR value of the upper-storey trees decreased compared to the protected forest. The explanation for this can be the creation of gaps, which allow more light to reach the trees on the lower storey. The results showed that the amount of LCR of light-demanding tree species such as maple and alder increased, and the amount of LCR of shade-tolerant tree species such as beech decreased due to the implementation of selection cuttings. In fact, by creating a gap in the canopy of the forest and allowing more light to reach the canopy of the light-demanding trees, the amount of their LCR increased.

This can be also due to the reduction in tree diameter diversity (TDD), which could also reflect a reduction in age, species diversity indices, THD, and increasing HDR in the managed stand compared to the control stand, as already discussed. The tree crown houses physiological processes that are fundamental to tree growth. The relationships of neighbouring and even competition between trees are reflected in the size and interpenetration of the crowns. In fact, forest managers pay particular attention to maintaining regular diametrical growth to ensure stems that have growth rates for obtaining quality timber, adjusting the density of the stand on the basis of the light factor. In this sense, the live crown ratio (LCR) can give an indication of the tree's ability to grow in diameter. The values found are similar to those given in the literature as an indication of adequate growth [27]. In the protected parcel, the LCR is higher than in the selection cutting parcel, reflecting the differences between them in terms of tree density and stand volume.

4.3. Relationship between Stand Structure and HDR and LCR

Resilience is the capacity of forests to maintain essential characteristics of taxonomic composition, structure, ecosystem functions, and processes when challenged by disturbances. It is dependent on biodiversity at multiple levels [89]. Management, both passive and active, can increase or decrease the vulnerability of forests to climate change [90,91]. The stand structural complexity index (SCI) is used to compare the results of different management system settings. Tree and stand characteristics change over time, and thus, various empirical forest models including HDR models are necessary to update the information on these characteristics. Our results indicated that there is a significant negative relationship between height-to-diameter ratio (HDR) and live crown ratio (LCR) indices, as expected, given that a longer crown corresponds to greater stability. Wang et al. [92] also reported the tree HDR index decreased with increasing tree DBH, height, age, and crown length, which are in line with our results. The HDR index had a significant positive correlation with the stand structural complexity index (SCI). Also, the LCR had a significant positive correlation with SCI. Several studies used the tree HDR index for tree and stand stability and vulnerability to natural disasters [93]. The HDR information is essential for better understanding forest ecological processes in any forest as HDR is substantially influenced by tree species, stand age, stand structure, stand density, site quality, stand development stage, and silvicultural tending [94,95]. The HDR also varies with tree root system, crown width, and crown length [82]. Among the above-mentioned factors, inter-tree spacing, competition, and stand density have the biggest influences on HDR [96–99]. In line with our results, Põldveer et al. [100] in the Estonian forests reported that the SCI is positively associated with commonly measured stand characteristics, indicating that the stand structural heterogeneity reflected in SCI is higher for older stands with larger trees, higher deadwood quantity, and biomass. Trees with a larger HDR are always associated with an increased risk of vulnerability to uprooting by windstorms and breakage by windstorms and ice [83,101–103].

5. Conclusions

This research analysed the effects of selection cutting management on stand structure and tree growth form in mountain-mixed beech forests over a period of almost 50 years, put it in comparison with a purely conservative form of forest management (forests with a history of protection). With awareness of the importance of 360° sustainable forest management, which does not underestimate the economic and social aspects related to forestry, from this study it was possible to obtain reflections and possible applicable and acceptable sylvicultural suggestions related to selection cutting.

Generally, selection cuttings generate release space and give more light to the understory trees, and this, if well managed, leads to greater specific diversification and a higher growth in the height of the new trees. However, these results, when analysed through more complex and multidisciplinary indices, highlighted—for the selection cutting areas—the decrease in the number of canopy layer species, the tree diameter, and the tree height diversity indices. The lower value of these indices together with the lower tree species richness index of the canopy layer caused a decrease in the stand structural complexity index (SCI). This more complex vision suggests more sensible silvicultural criteria for the choice of trees to cut, such as greater specific diversification of medium- and large-size trees to be released and careful evaluation of the preservation of the old trees.

Moreover, the results of this study suggest that future forest management should aim to increase the volume of stand and deadwood, in order to increase the structural complexity and species diversity in these forests.

Another important issue was highlighted, related to the increase in the height-to-diameter ratio (HDR) of trees, as a result of selection cutting management, which may reduce the stability of these forests against the risk of snow and wind damage. In this case, the sylvicultural suggestion is to further pay particular attention in selecting the trees to be cut on the edge of these stands and on exceedingly steep slopes; reducing the competition between trees will increase the stability of these stands against the snow and wind.

Awareness and knowledge of these indices and indicators and their reading in relation to medium–long-term site-specific studies will allow the forest manager to guarantee and improve the sustainability of these complex environments.

Author Contributions: Conceptualization, S.K., M.N., K.T.A. and F.T.; Data curation, S.K., M.N. and R.P.; Formal analysis, S.K., M.N. and K.T.A.; Investigation, S.K. and K.T.A.; Methodology, S.K., M.N., K.T.A. and F.T.; Supervision, F.T., A.L.M. and R.P.; Validation, M.N., K.T.A., F.T. and R.P.; Visualization, A.L.M.; Writing—original draft, S.K., M.N., K.T.A., F.T., A.L.M. and R.P.; Writing—review and editing, F.T., A.L.M. and R.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are available upon request from the corresponding author.

Acknowledgments: The research was carried out within the framework of the Ministry for Education, University, and Research (MIUR) initiative "Department of Excellence" (Law 232/2016) DAFNE Project 2023-27 "Digital, Intelligent, Green and Sustainable (acronym: D.I.Ver.So)"—UNITUS-DAFNE WP3.

Conflicts of Interest: The authors declare no conflict of interest.

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