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RESEARCH PAPERS

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LONG-TERM IMPACT OF SELECTION CUTTING MANAGEMENT ON FREQUENCY OF STEM DEFORMITY IN MIXED BEECH FORESTS OF NORTHERN IRAN

The aim of this study was to evaluate the long-term effect of selection cutting management on the stem quality of the trees remaining in the forest. For this purpose, three parcels managed for three decades by selection cutting were selected as managed stands (MP), and two protected parcels without tree felling as control stands (PP). First, the frequency of deformed stems in each parcel was determined for a circular 1000 m^2 area of each plot by systematic sampling of 100 m × 100 m grid sections, and then a stem deformity index was estimated for each of the deformed stems.

The results showed that the frequency of stem deformity in MP (6.5%) was significantly lower than in PP (20.7%) ($p < 0.01$). In addition, the frequency of all types of stem deformities in MP was significantly lower than in PP. Furthermore, selection cutting management reduced the indices of twisting, decay, conicity, forking, and ellipticity by 58.4%, 53.9%, 34.7%, 8.4% and 6.8%, respectively. The results for the correlation between frequency of stem deformity and tree diameter at breast height (dbh) showed that the curves followed a parabolic shape in both MP (r = 0.83) and PP (r = 0.80), where the frequency of deformed stems decreased with increasing dbh (up to 75 cm in MP, and up to 65 cm in PP), and then increased with larger dbh. Selection cutting management, regardless of tree species, improved the stem form. Decay accounted for a high proportion (24.1%)

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of the total deformity in MP, mainly due to logging damage. Overall, the results of this study show that selective management has been successful in improving the quality of tree boles in the studied mixed beech stands. Regular and long-term stand monitoring and statistical quality control (SQC) may be a good approach to aligning ecological and economic goals in forest management.

Keywords: stem form, stem deformity indices, log defects, mixed beech stands, silviculture effect, statistical quality control (SQC)

Introduction

Preservation of biodiversity, natural regeneration of trees, improvement of the quality and quantity of stands, application of continuous cover forestry, and regularity in wood production are the main objectives of selection cutting in a sustainable forest management system [Vusić et al. 2013; Tavankar et al. 2019a]. The northern forests of Iran have been managed for the past three decades by the selection cutting method. One of the important objectives of forest management has been to pay close attention to the shape of the stems of standing trees in terms of health and wood quality, more frequently assessed as cylindricity [Del Río et al. 2004].

The shape of tree stems can be classified into two main general types: no deformity and deformity. The main types of deformities found in forest trees are as follows: stem with sinuous, leaning, bending, forking and conical shape; with elliptical or irregular section; with twisting and decay [Turvey et al. 1993; Spicer et al. 2000; Leduc et al. 2012; Zeltinš et al. 2018]. Genetic, ecological and silvicultural factors influence the creation and frequency of stem deformity in forests [Del Río et al. 2004]. Sometimes, environmental characteristics highlight genetic features of certain origins [Duchemin et al. 2018].

Snow and wind are believed to be the most important environmental factors in creating stem deformity in forest trees [Timell 1986; Del Río et al. 2004; Dinulica et al. 2016]. The effect of these two factors results from an asymmetrical dislocation of the loads applied to the cylindrical stems, which causes curvature, especially on steep slopes [Timell 1986]. Frequent frosts have also been reported as causes of deformity, and especially forking, of tree stems in the early stages of tree growth (seedlings and large seedlings) [Ningre and Colin 2007]. Light stimulates the growth of the crowns [Sone et al. 2005; Williams et al. 2019] and the effect is well known on edge trees and on codominant or dominated trees within the forest [Sierra de Grado et al. 1997]. Insect attacks, fungal diseases, injury by herbivores grazing on the apical shoots of young trees, and mechanical disturbance (rock fall, debris flow, etc.) are other ecological factors that contribute to the creation of deformities in forest trees [Del Río et al. 2004]. The response of forest trees to environmental factors, such as strong wind and snow, as well as solar radiation in forests, is influenced by the stand characteristics. Reactions to environmental factors vary according to the silvicultural characteristics of the stand. Stand and tree characteristics can be modified by thinning, and quality can be improved by selecting trees on the basis of morphological features [Del Río et al. 2004], so as to increase the stumpage value and the financial return [Jokela et al. 2010].

Deformity in trees causes defects in logs and affects the timber grade [Tavankar et al. 2017a]. Stem curvature, usually associated with the presence of compression wood, certainly diminishes timber quality [Aldohus 1986; Del Río et al. 2004]. Sinuous growth in young Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco) is a conspicuous stem deformity which is most noticeable in young plantations [Gartner and Johnson 2006]. The causes of sinuosity and associated growth patterns are not well understood. The degree of sinuosity of the tree stem not only changes with the growth of the tree over time, but also varies between different parts of the stem [Spicer et al. 2000]. Genetic, biomechanical, nutritional, and vegetative factors influence the occurrence of stem sinuosity in radiata pine (*Pinus radiata* D. Don) [Turvey et al. 1993; Downes et al. 1994]. Individual radiata pine trees that have a higher rate of height growth are more susceptible to stem sinuosity formation [Downes and Turvey 1990; Downes et al. 1994]. In contrast, a higher rate of height growth was not the main cause of stem sinuosity formation in Douglas-fir [Gartner and Johnson 2006].

There are indications that planting distance contributes to elliptical cross--section of stems in plantations [Mäkinen 1998]. Elliptical cross-section is also caused by the asymmetric effect of the tree crown [Kashkouli et al. 2007]. Elliptical cross-section reduces wood quality and decreases sawing yield [Kashkouli et al. 2007; Fallahnia and Rafighi 2012]. Environmental and genetic factors influence the formation of stem forking [Salehi Shanjani et al. 2011; Zeltinš et al. 2018]. Stem forking is generally due to frost in the early years of beech life [Ningre and Colin 2007]. Forking, in addition to reducing the length of the tree stem, reduces tree quality [Drénou 2000]. Beech (*Fagus orientalis* Lipsky) seedlings are very susceptible to late frost. Frost in beech seedlings reduces the height growth and induces stem deformity in later stages [Hristov and Botev 1981]. The distance between trees increased with the thinning operation and selection cuttings, and as a result the crown and trunk diameter increased. This can cause changes in the stem form. Stem deformity increases logging costs, while the commercial value of the wood produced is reduced.

One of the important goals of forest management is to derive economic benefits. Forest management has traditionally been aimed at producing quality timber for industry, and trees with defects are systematically eliminated. Deformed trees that have no economic future will be cut down and removed from the forest by various sanitary/selection cuttings during the forest management period to provide a better space for other trees to grow. In this framework, the objectives of this study were: I) to determine the frequency of stem deformity, and II) to estimate indices of stem deformity in the long-term managed stands subject to selection cutting and in control stands, and thus to indicate the effect of forest management on timber quality.

Materials and methods

Study area

This study was carried out in the forests of Talesh city in Gilan province in northern Iran. Districts 1, 2 and 3 of the Nav forests were designated as study areas, having geographic coordinates between 48° 33' and 49° 1' E and between 37° 31' and 37° 45' N. The climate of the region is in the wet group based on De Martonne's moisture coefficient classification. The mean annual precipitation is 924 mm and the mean annual temperature is about 10.2°C [Tavankar and Nikooy 2017a]. Three selection cutting managed parcels (MP), 99 ha in total, and two protected parcels (PP), 97 ha in total, were selected for the study (Table 1). In the managed parcels, harvesting was performed over three 10-year periods, while no harvesting was performed in the control parcels (PP). The physiographic and silvicultural characteristics of the studied parcels are shown in Table 1.

Table 1. Some of the physiographic and silviculture characteristics of the study area (MP: selection cutting managed parcel, PP: protected parcel)

Parcel number	Area (ha)	Altitude a.s.l. (m)	Ground slope (%)	Management method	Composition of tree species (%)
330	27	1350-1420	34.5	MP	beech (68), alder (10), hornbeam (8), maple (6), other (8)
331	35	1250-1380	30.3	MP	beech (73), hornbeam (11), maple (5), alder (3), other (8)
223	31	1280-1390	23.6	MP	beech (56), maple (22), hornbeam (11), alder (7), other (4)
123	35	850-1050	25.9	PP	beech (46), maple (28), hornbeam (19), alder (4), other (3)
340	62	1580-1460	32.8	PP	beech (40), maple (27), hornbeam (25), alder (5), other (3)

Data collection

Frequency of stem deformity was estimated through systematic plot sampling. The grid dimensions were 100 m × 100 m, the shape of the plots was circular, and the area of each plot was 1000 m^2. Diameter at breast height (1.30 m; dbh) of all trees (dbh ≥ 7.5 cm) was measured using a dendrometric caliper. Tree stems in each plot were placed in two categories – deformity and no deformity – according to the form and appearance of the stem. Deformities were classified according to the following eight types: sinuosity (SI), leaning (LI), bending (BI), forking (FI), taper (conicity) (CI), ellipticity (EI), twisting (TI) and decay (DI), and their deformity index was measured (Table 2, Fig. 1).

Table 2. Indicators and indices used to assess stem deformity

Equation number	Stem deformity index (reference)	Equation
(1)	Sinuosity index (SI), (Leduc et al. 2012)	$SI=\frac{L}{A}$
(2)	Leaning index (LI), (Leduc et al. 2012)	$LI=\frac{L}{H}$
(3)	Bending index (BI), (Leduc et al. 2012)	$BI=\frac{A}{D}$
(4)	Forking index (FI), this research	$FI=\sum n_f$
(5)	Conicity index (CI), (Tavankar et al. 2019a)	$CI=\frac{dbh}{H}$
(6)	Ellipticity index (EI), this research	$EI=\frac{dbh_l}{dbh_s}$
(7)	Twisting index (TI), this research	$TI=\frac{L_t}{L}$
(8)	Decaying index (DI), (Tavankar and Nikooy 2017b)	$DI=\frac{V_d}{V}$
(9)	Shortest line length (A), this research	$A=\sqrt{H^2+D^2}$
(10)	Stem length (L), this research	$L=0.785\times\sqrt{2(H^2+D^2)}$
(11)	Decay volume (Vd), (Tavankar and Nikooy 2017b)	$V_d=(d_1+d_2)^2\times0.1962\times L_d$
(12)	Stem volume (V), this research	$V=0.49455\times(DBH)^2\times H$

where L is the stem length (m), calculated by Eq. 10; A is the shortest line length from base to tip (m), calculated by Eq. 9; H is the stem height (m), measured by a clinometer; D is the distance between the base and the vertical line from tip to ground level (m), measured by a tape; n_f is number of branches diverged from the main stem; dbh is the diameter at breast height (cm), measured by a dendrometric caliper; dbh_l is the larger stem diameter at breast height (cm); dbh_s is the smaller stem diameter at breast height (cm); L_t is the stem length that has been twisted (m); V_d is the decayed volume (m^3), calculated by Eq. 11; V is the stem volume (m^3), calculated by Eq. 12.

The structure of both managed and protected stands is uneven-aged mixed high forest. In the managed stands, selection cutting had been performed three times (once every 10 years). The volume of timber harvested in each cutting operation was 10 to 20 m^3 ha^{-1} and the dbh of the trees was from 30 to 145 cm. The objectives of the selection cuttings were to reform the forest structure, to assist the natural regeneration of trees, and to derive economic income. These selective cuts are versatile; defective trees (decayed and deformed stems) are also felled and removed from the forest at the same time as the felling and extraction of crop trees.

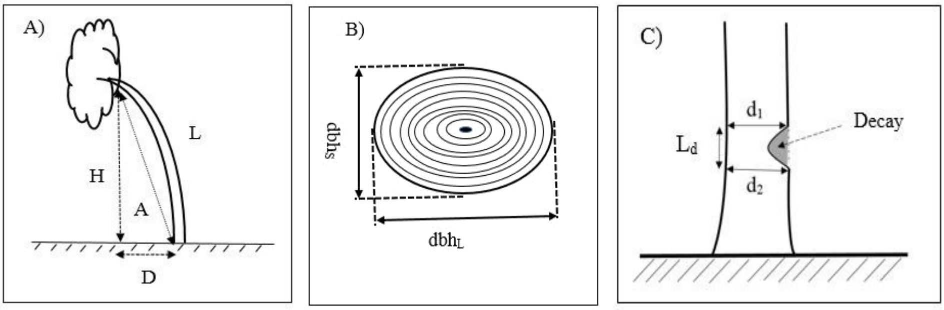

Fig. 1. Stem parameters for the estimation of A) SI, LI, and BI, B) EI, and C) DI

Data analysis

Data were analyzed using SPSS version 19 software (IBM, NY, USA) and charts were drawn using Excel and CurveExpert software. At first, data normality was checked by the Kolmogorov-Simonov test, and homogeneity of variances was checked by Levene's test. The means of dendrometric stand characteristics (tree density, basal area, and stand volume) and stem deformity frequencies in the studied parcels were compared by ANOVA, then significant differences between means were separated by Duncan's test at $\alpha = 0.05$. The means of stem deformity indices in MP and PP were compared using an independent samples t-test. Frequencies of stem deformity types were compared in MP and PP and among tree species using a non-parametric chi-square test. Correlation between frequencies of stem deformity with tree dbh was investigated by nonlinear regression.

Results

Standing volume

In the study parcels, tree density ranged from 211 to 279 stem·ha^{-1}, basal area from 24.3 to 30.5 m^2·ha^{-1} and stand volume from 184.5 to 257.3 m^3·ha^{-1} (Table 3). ANOVA results showed that the means of all three forest characteristics in the studied parcels were significantly different. The highest tree densities were in PP-123 (279.2 stem·ha^{-1}) and MP-231 (277 stem·ha^{-1}); the highest basal area was in MP-231 (30.5 m^2·ha^{-1}); and the highest stand volumes were in PP-123 (257.3 m^3·ha^{-1}) and MP-231 (250.4 m^3·ha^{-1}).

Table 3. Mean (± SD) of tree density, basal area, and stand volume in the study parcels (MP: selection cutting managed parcel, PP: protected parcel), and the results of ANOVA and Duncan's test

Parcel	Management method	Plot N	Tree density (stem·ha^{-1})	Basal area (m^2·ha^{-1})	Stand volume (m^3·ha^{-1})
230	MP	24	248.7 ±15.2 c	25.2 ±5.0 b	214.6 ±30.4 b
231	MP	30	277.0 ±18.6 a	30.5 ±4.7 a	250.4 ±26.6 a
223	MP	28	211.6 ±13.4 d	24.3 ±4.6 b	184.5 ±22.0 c
123	PP	32	279.2 ±17.1 a	26.5 ±4.7 b	257.3 ±27.9 a
340	PP	56	263.9 ±11.8 b	24.9 ±3.8 b	210.4 ±23.5 b
ANOVA					
F-value	–	–	90.938	13.277	82.818
p-value	–	–	0.000	0.000	0.000

Stem deformity in selection cutting managed (MP) and protected parcels (PP)

ANOVA and Duncan's test showed that the frequency of stem deformity in MP was significantly lower than in PP (Table 4). Trees showing stem deformity accounted for 5.7% to 7.4% of total trees in MP and 20.6% to 20.7% of total trees in PP (Table 4). The frequency of trees with stem deformity was about 3-4 times higher in PP than in MP.

Table 4. Frequency of stem deformity (mean ± SD) in study parcels (MP: managed parcel; PP: protected parcel), and the results of ANOVA and Duncan's test

Parcel – management method	Total number of sampled stems	Deformity stems (%)
230 – MP	596	5.7 ±2.9 b
231 – MP	831	7.1 ±3.3 b
223 – MP	592	7.4 ±4.0 b
123 – PP	893	20.7 ±3.9 a
340 – PP	1474	20.6 ±3.4 a
ANOVA		
F-value	–	159.482
p-value	–	0.000

ANOVA results indicated significant differences in the mean frequency of stem deformity types both in MP ($F = 24.902$; $p < 0.01$) and in PP ($F = 36.041$; $p < 0.01$). Based on Duncan's test, the mean frequency of the eight types of stem deformity in PP was significantly higher than in MP ($p < 0.05$) (Fig. 2). The stem deformity with the highest frequency was decay, in both PP and MP (3.68%

in PP and 1.63% in MP). The lowest-frequency stem deformity type was elliptical cross-section in PP (1.64%) and twisting in MP (0.2%). The frequency of sinuous stems in PP (2.79%) was about three times as high as in MP (0.94%). The frequency of twisted stems in PP (2.15%) was about 11 times as high as in MP. The frequency of forked stems in PP (1.2%) was almost twice as high as in MP (0.64%). After decay, the main deformity type in PP was conicity (3%), which was three times as frequent as in MP (0.89%). The frequency of leaning stems was also about twice as high in PP (2.1%) as in MP (1.1%).

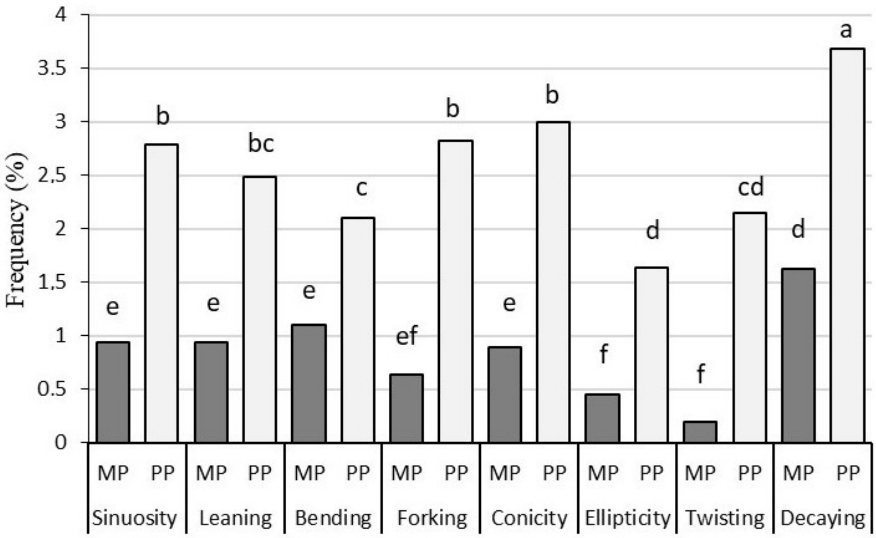

Fig. 2. Mean frequency of stem deformity types in the selection cutting managed parcel (MP) and in the protected parcel (PP). Different letters indicate significant difference between MP and PP by Duncan's test at α = 0.05

Distribution of stem deformity in dbh classes

The results showed that the frequency of deformity was higher in small-diameter (dbh < 30 cm) and large-diameter (dbh > 100 cm) trees than in medium-diameter trees (dbh 30-100 cm), in both MP and PP (Fig. 3 A, B). The frequency of deformity was found to decrease with increasing tree dbh up to 75 cm in MP and up to 65 cm in PP; it then increased with larger dbh.

A nonlinear regression test showed a significant correlation ($p < 0.01$) between the frequency of deformity of stems and dbh (Eq. 13 for MP, Eq. 14 for PP).

$$y = 2.895669 - 0.025220(x) + 0.000236(x)^2 \quad (13)$$

$$SE = 0.515; \; R^2 = 0.65; \; F = 16.478; \; p = 0.000$$

$$y = 1.114969 - 0.016103(x) + 0.000128(x)^2 \quad (14)$$

$$SE = 0.201; \; R^2 = 0.69; \; F = 22.311; \; p = 0.000$$

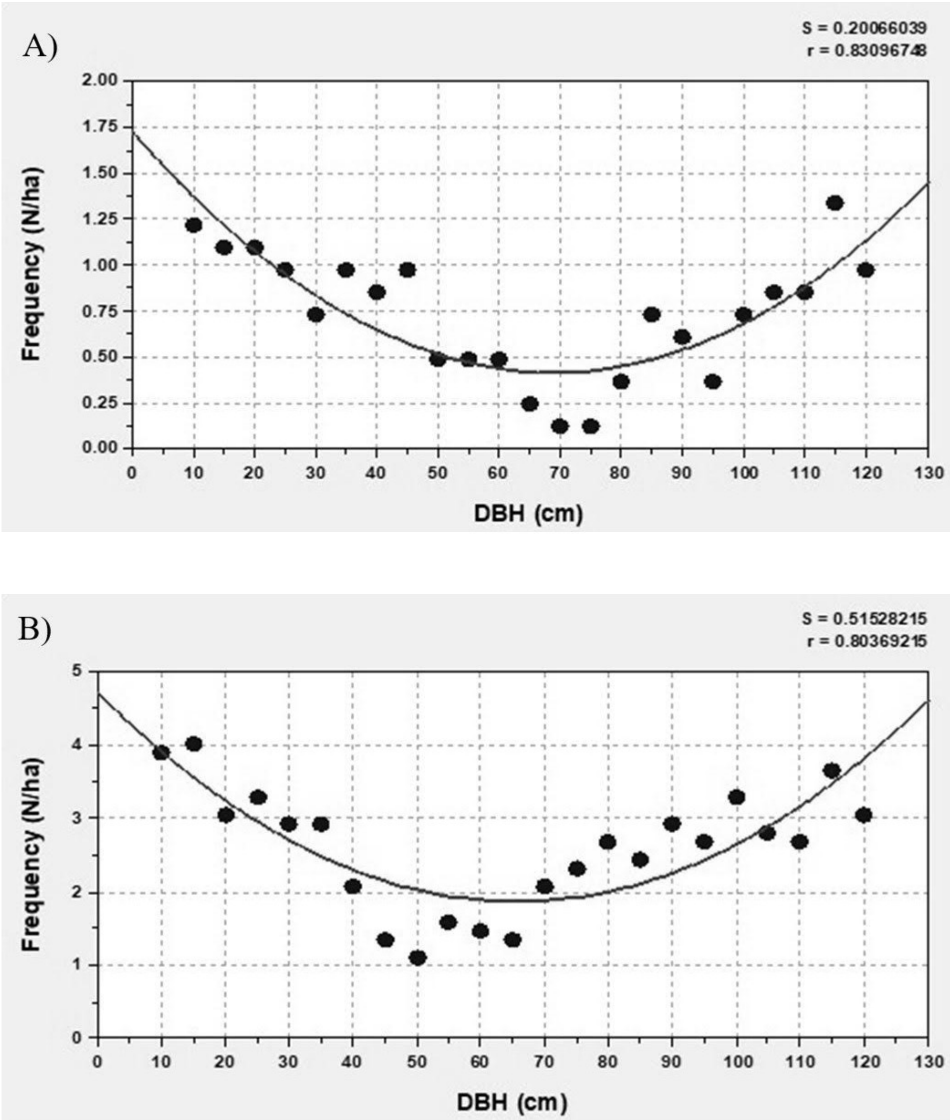

Fig. 3. Stem deformity distribution by trees dbh (A: selection cutting managed; B: protected). r is the correlation coefficient, and S is the standard error

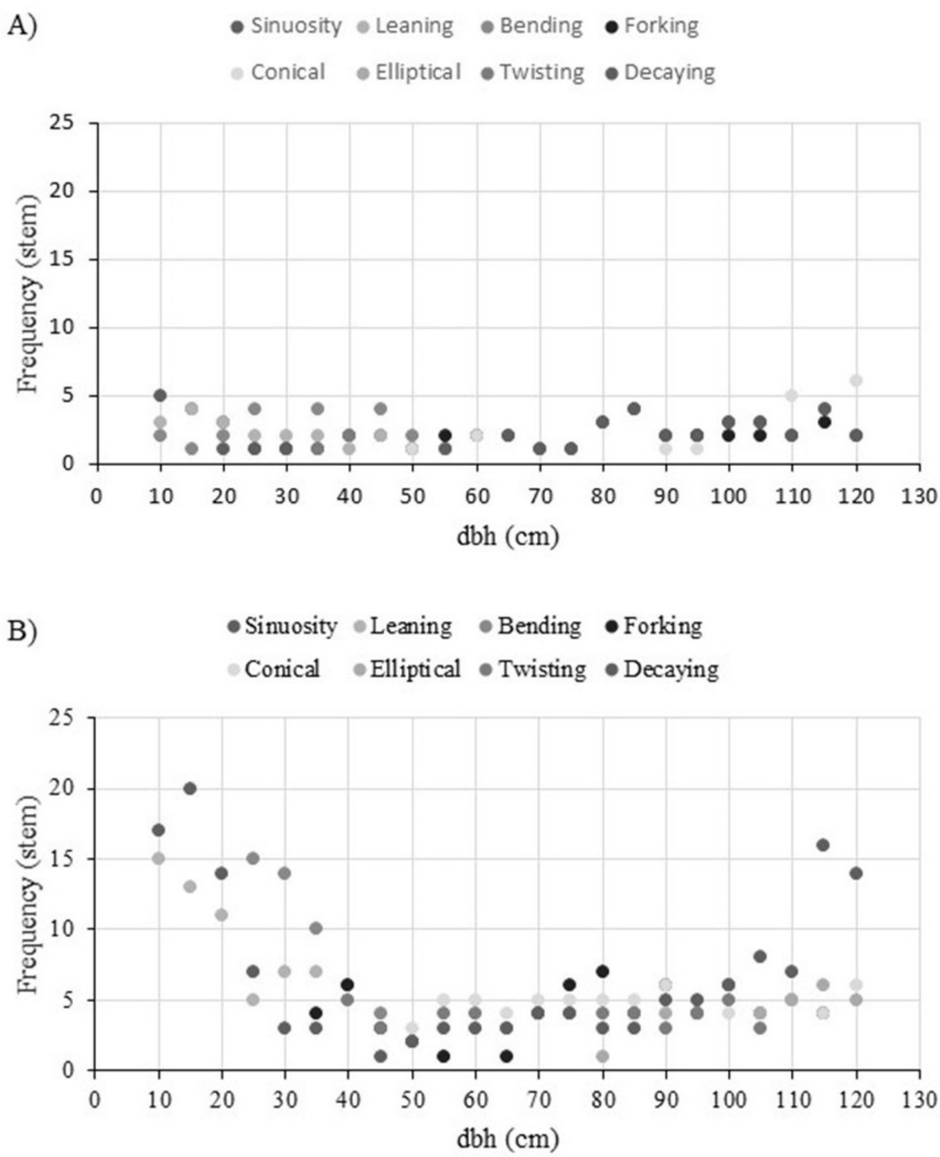

Fig. 4. Frequency of stem deformity types in the parcels (A: selection cutting managed parcels, MP; B: protected parcels, PP)

The highest frequencies of sinuous, leaning and bending stems were observed in small-diameter trees (Fig. 4). The frequencies of sinuous, leaning and bending stems decreased with an increase in tree dbh. The sinuosity, leaning and bending deformity types were not found in trees with dbh greater than 50 cm.

Decayed stems were observed more frequently in higher dbh classes. Forked stems were observed in dbh classes from 35 to 115 cm in PP, and from 55 to 115 cm in MP. The highest frequency of forked stems was observed in the 80 cm dbh class in PP, and in the 115 cm class in MP.

Stem deformity in tree species

The frequency of deformed stems of beech, hornbeam, maple, and alder in protected stands (PP) was significantly higher than in MP ($p < 0.01$) (Table 5). The highest frequency of stem deformity in PP was observed in alder (25.2%), while in MP the highest frequency was observed in hornbeam (12.6%). Beech stems had the lowest frequency of deformity (4.2%) in MP.

Table 5. Stem deformity frequency per tree species, and management type (MP: selection cutting managed parcels; PP: protected parcels), and results of chi square tests

Tree species	Management	Total sampled stems n	Deformed stems n	Frequency of deformed stem (%)	Chi square value
Beech	PP	982	185	19.8	129.8**
	MP	1332	56	4.2	
Hornbeam	PP	631	124	23.3	13.1**
	MP	270	34	12.6	
Maple	PP	649	132	20.3	8.9**
	MP	232	25	10.8	
Alder	PP	103	26	25.2	11.0 **
	MP	161	16	9.9	
Other	PP	102	28	27.4	0.06 NS
	MP	24	6	25.0	

Beech

The total number of deformed beech stems was 56 in MP and 185 in PP; the frequency of deformed beech stems in PP (19.8%) was about five times as high as in MP (4.2%) (Table 5). The chi-square test showed a significant difference in the frequency of deformity types in both MP and PP (Fig. 5a). Figure 5a shows the frequency of deformities in beech in PP and MP. In PP, conicity had the highest frequency. However, the frequency of decayed stems in PP was also high. Decayed stems had the highest frequency in MP (32.1%), while conical stems accounted for 12.5% (7 stems) of the total number of deformed beech stems. The frequency of sinuous beech stems in MP was lower than in PP, but the frequency of leaning beech stems was higher in MP than in PP (10.7% vs. 8.7%). Bending beech stems in PP were three times as numerous as in MP, but the frequencies were similar (respectively 13.0% and 14.0%). Forked beech stems accounted for 10.7% of total deformed beech stems in MP and 14.1% in PP. Twisted beech stems had a lower frequency in MP than in PP.

Hornbeam

The number of deformed hornbeam stems was four times as high in PP as in MP (Table 5), but the frequency of deformed stems in PP was 2.5 times greater than in MP. The chi-square test (Fig. 5b) showed a significant difference among the frequencies of deformity types in hornbeam stems in PP, but no significant difference in MP. Decayed hornbeam stems were the most frequent in both stand types (29.4% in MP and 21.0% in PP). Conical stems were more frequent in MP (20.6%) than in PP (16.1%). The frequencies of sinuosity and leaning in hornbeam were higher in MP (14.75% and 8.8% respectively) than in PP (10.5% and 6.4%), but the frequency of bending hornbeam stems was lower in MP (5.9%) than in PP (11.3%). The frequency of forked hornbeam stems in PP (17.7%) was about three times as high as in MP (5.9%).

Maple

The number of deformed maple stems was five times as high in PP as in MP (Table 5). The chi-square test showed a significant difference in the frequency of deformity types in both MP and PP (Fig. 5c). Unlike in the case of beech, hornbeam and alder, decayed maple stems did not appear in MP. Of total stem deformities in PP, 13.6% were of the decaying type (Fig. 5c). Maple stems with twisting and with elliptical cross-section were not observed in MP, while the frequencies of these types of deformities in PP were 8.3% and 4.8% respectively. The most frequent maple deformities were bending (32%) and leaning (28%) in MP, and leaning (26.5%) and sinuosity (18.9%) in PP. The frequency of forked stems in MP (20%) was higher than in PP (14.4%), and the frequency of conical maple stems in MP (4%) was slightly lower than in PP (5.3%).

Alder

The number of deformed alder stems was 1.6 times higher in PP than in MP (Table 5). The chi-square test (Fig. 5d) indicated a significant difference among the frequencies of deformity types in alder stems in PP, but no significant difference in MP. Out of the total number of deformed alder stems, the decaying type had the highest frequency (31.3%) in MP, while the ellipticity type had the highest frequency (26.9%) in PP (Fig. 5d). The frequency of bending stems was 25.0% in MP. The elliptical cross-section, forking and twisting types of deformities were not observed in MP, and sinuous, leaning, and bending stems were not observed in PP.

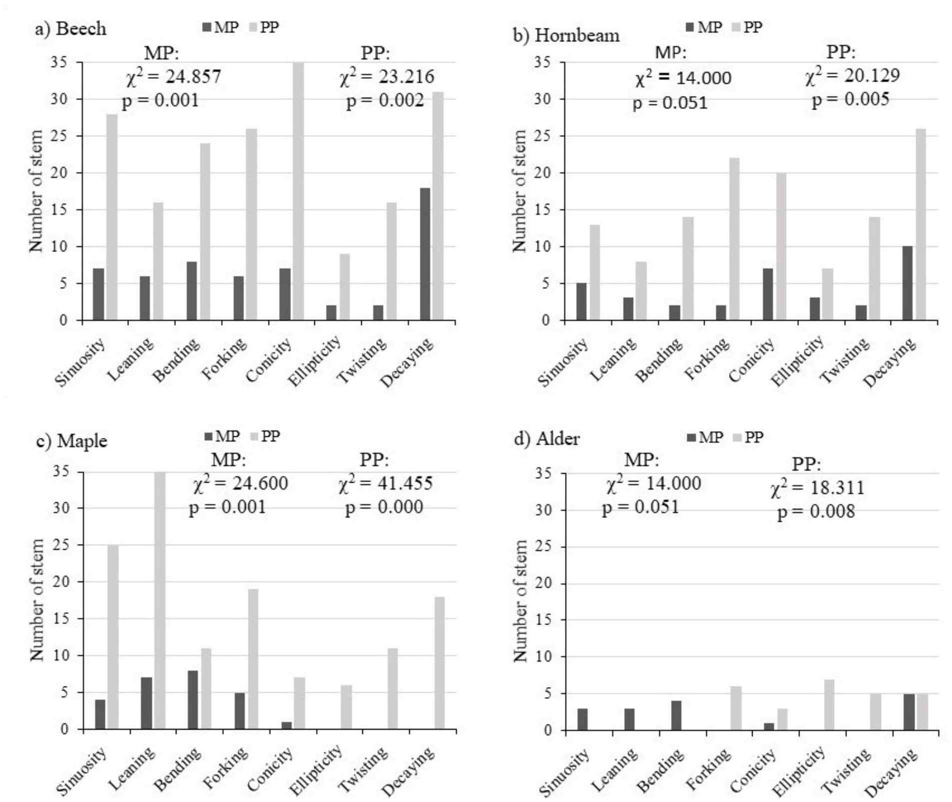

Fig. 5. Frequency of stem deformity types in tree species, in protected (PP) and managed (MP) parcels, and results of chi-square tests

Values of deformity indices

The mean sinuosity index (SI = 1.10) and the mean leaning index (LI = 1.12) were similar in both MP and PP, and no significant differences were detected (Table 6). The mean forking index was also not statistically different in MP (FI = 2.23) and in PP (FI = 2.66).

The mean bending index was significantly (at $\alpha = 0.05$) higher in MP (BI = 5.94) than in PP (BI = 5.05), while the mean ellipticity index was significantly higher in PP (EI = 1.21) than in MP (EI = 1.13) (Table 6).

The mean conicity index was significantly (at $\alpha = 0.01$) higher in PP (CI = 6.10) than in MP (CI = 3.95); the mean twisting index was also significantly higher in PP (TI = 0.11) than in MP (TI = 0.05); similarly the decay index was statistically higher in PP (DI = 0.06) than in MP (DI = 0.03) (Table 6).

Table 6. Stem deformity indices (mean ± SD) in parcels (PP: protected parcels; MP: selection cutting managed parcels) and results of t tests

Index of stem deformity	Parcel	No. of stem	Mean ± SD	t – value	p-value
Sinuosity (SI)	PP	66	1.097 ±0.008	0.785	0.450 NS
	MP	19	1.098 ±0.007		
Leaning (LI)	PP	59	1.124 ±0.008	0.770	0.443 NS
	MP	19	1.123 ±0.007		
Bending (BI)	PP	49	5.054 ±1.197	2.406	0.014*
	MP	22	5.940 ±1.842		
Forking (FI)	PP	67	2.327 ±1.008	0.785	0.385 NS
	MP	13	2.660 ±1.055		
Conicity (CI)	PP	71	6.097 ±2.219	3.697	0.000**
	MP	18	3.950 ±1.954		
Ellipticity (EI)	PP	39	1.212 ±0.085	2.697	0.010*
	MP	9	1.129 ±0.072		
Twisting (TI)	PP	51	0.109 ±0.046	2.733	0.009**
	MP	4	0.045 ±0.021		
Decaying (DI)	PP	87	0.060 ±0.018	4.385	0.000**
	MP	33	0.028 ±0.009		

*significant at α = 0.05; **significant at α = 0.01, NS: not significant.

The values of stem deformity indices in MP compared with PP showed the following changes: twisting decreased by 58.4%, decay decreased by 53.9%, conicity decreased by 24.7%, forking decreased by 8.4%, the elliptical index decreased by 6.8%, and the bending index increased by 14.9%.

Discussion

The effect of management on frequency and diameter distribution of stem deformity

The frequency of deformity in MP was three to four times lower than in PP. Observing the frequency of stem deformity for dbh classes, it was found to be lower in MP than in PP, confirming that deformity is homogeneously distributed in both MP and PP. In fact, with the implementation of three periods of selection cutting in MP, which covers a period of 30 years, the quality of trees remaining in the forest was improved and the frequency of deformity was significantly reduced. The reason may be that the selection cutting management is based on the classical goals of the management approach in the study area, to produce high quality lumber for industry. On the one hand, by cutting out the deformed trees, the frequency of deformities was reduced, and on the other hand, this intervention provided environmental conditions for the growth of better-quality trees, improving diameter growth.

The frequency of all types of deformities was significantly lower in MP than in PP. The initial spacing of stems in stands affects competition between trees for sunlight, moisture, and nutrients, and therefore influences tree growth patterns and wood formation [Macdonald and Hubert 2002]. Forest management plays a key role in tree stem development [Amaral et al. 2019]. Selection cutting of trees by modifying light and reducing tree crown competitiveness reduced the frequency of sinuous, leaning and bending stems and favored diameter growth, improving the quality of the remaining tree boles. Villela et al. [2006], in the Brazilian Atlantic forest, indicated that the profile diagrams of unlogged and selection logged stands showed differences in canopy structure, mainly in height and in crown connectivity. Forking stems were cut during selection cutting management and the incidence of this type of deformity decreased. Selection cutting management reduced decaying stems by the extraction of large decaying trees during the three rotation periods. Although decaying stems were found in MP (1.63% of the remaining trees), they were mostly caused by mechanical damage to the residual trees during logging operations [Tavankar and Nikooy 2017b]. This type of deformity mainly depends on harvesting activities and can therefore be reduced with better organization of work in the forest and with correct planning of felling and logging works. The greatest damage often occurs along the skid-trails; therefore, adequate worker training can reduce the incidence of this serious defect, as well as other negative impacts [Vasiliauskas 2001; Picchio et al. 2016].

Tests of correlation between frequencies of stem deformity and tree dbh showed that the curve followed a parabolic shape in both MP and PP. In fact, the frequency of stem deformity was high in both thin and thick trees, and lower in moderate diameters, in both stand types. Stem deformity in trees with lower dbh was due to a higher frequency of sinuous, leaning and bending stems, while in trees with high dbh it was due to a higher frequency of conical and decaying stems, in both stand types. Tavankar et al. [2019a] observed bending caused by snow in the lower diameter classes and noted an increase with height and slenderness coefficient. On leaning stems, rings are often characterized by a localized zone of abnormally wide growth thickness that causes the pith to be off-center [Walker 2006]. This is thought to develop due to stress on the stem, namely gravity, but is also found to be produced in juvenile wood of trees experiencing rapid height growth [Barnett and Jeronimids 2003]. Reaction wood has different anatomical, chemical, and physical characteristics than normal wood [Plomion et al. 2001; Walker 2006].

Although the presence of stems damaged by timber harvesting operations in managed forests is detrimental to the quality of the subsequent harvest, the presence of large individuals with decay can be considered positive in the context of sustainable and careful management of biodiversity conservation.

A careful choice of trees affected by decay which have a low market value for the production of quality wood, but are of large diameter, to be designated for indefinite aging makes it possible to create a reserve of habitat trees and to produce deadwood, useful for biodiversity conservation and the slow release of carbon [Tavankar et al. 2018; Lo Monaco et al. 2020]. The tradition of removing the poorest trees and leaving the best does not always enhance non-commodity values, such as wildlife habitat for cavity-associated species [Kenefic and Nyland 2007].

Frequency of stem deformity in tree species

The frequency of deformity in the four tree species examined (beech, hornbeam, maple and alder) was lower in MP than in PP. In fact, selection cutting management improved the stem quality regardless of tree species. This is linked to the nature of selection cutting management, which preserves the structure, composition and diversity of tree species in the stand [Tavankar et al. 2019a]. Obviously, the frequency of stem deformity was affected by the type of management and tree species. Amaral et al. [2019] indicated that selective logging modifies the natural dynamics of the forest by increasing mortality, recruitment and growth rates of residual trees. In the case of beech, the decaying type in MP and the conicity type in PP were more frequent than other deformities. Given that beech is the most abundant tree species in both stand types, more stem decay in MP is caused by logging damage, especially bole wounds, than other forms of stem deformities. Complete wound closure can take more than 15 years in a beech forest managed with single-tree selection cutting [Tavankar 2019b], leaving the injured trees prone to attack by fungi and insects. Forking in young and understored beech is a consequence of the ability to survive in low-light conditions, producing a thin and flat crown with weak apical dominance. This temporary deformity can be overcome when the light conditions improve [Drénou 2000]. Sometimes the forking is due to mechanical breakage to the crown, and the tree is unable to restore apical dominance. Wind and heavy snow more frequently damage crowns at higher altitude [Tavankar et al. 2019a], contributing to permanent forking formation. Elliptical stems were the least frequent in both stand types (MP and PP). As noted by Liu et al. [2003], when the slenderness coefficient of a tree becomes very high, there is a possibility that the tree may be exposed to bending stress, inducing the formation of reaction wood, which can affect the technological properties and end use of the timber.

Species that require high levels of light for regeneration are predicted to undergo rapid growth to exploit canopy gaps and develop taller stems at the sapling stage for a given diameter than more shade-tolerant species [Iida et al. 2011]. In addition to tree density, site fertility, canopy degree and physiographic characteristics of the site (altitude, slope) and climate, age and tree species are the main factors influencing the form of tree boles in a stand. With increasing tree age conicity increases, and shade-intolerant species (pioneer and fast-growing species) have a less conical shape than shade-tolerant species [Loetch and Haller 1964; Dudzinska 2003; Nikinmaa et al. 2003; Socha and Kulej 2005]. Also, the shape of tree boles is influenced by the forestry practices carried out in the past [Macdonald and Hubert 2002; Lee et al. 2003]. As a result, single selection cuts with an increasing number of young trees and shade-intolerant species reduces the frequency of conical stems in MP as compared with PP.

In the case of hornbeam stems, there was no significant difference among the abundances of deformity types in MP, but in PP these differences were significant. This may be due to the fact that selection cutting management has reduced over time the frequency difference of all deformity types in MP, such as sinuosity, leaning, conicity, forking and ellipticity, whereas in PP the frequency of deformed stems has been maintained.

Maple and alder are pioneer and shade-intolerant species, while beech and hornbeam are shade-tolerant species. Sinuosity, leaning, and bending are more likely to occur in pioneer and shade-intolerant species than in shade-tolerant species [Wang et al. 1998; Liu et al. 2003; Tavankar et al. 2019a]. The frequencies of sinuosity, leaning, and bending of maple stems in both MP and PP were higher than those of other stem deformities.

In the case of alder stems, completely different frequencies of deformity were observed between the two management systems. The sinuosity, leaning and bending stem deformity types accounted for more than 60% of total deformities in MP, whereas no such deformity was observed in PP. However, forking, ellipticity and twisting were not observed on alder in MP. In addition, decay accounted for a large proportion of the total deformities in MP. As mentioned above, this is primarily due to the shade-intolerant and fast-growing behavior of this species, which prefers more open spaces in the forest, such as those close to roads and skidding trails which are likely to be affected by skidding and winching during logging operations [Tavankar et al. 2017b].

Values of indices

The results of this research indicate that the selection cutting management system not only reduced the frequency of all types of stem deformity compared with the protected parcels, but also caused a reduction of deformity indices. Forest managers have focused on silvicultural practices, including genetic improvements that maximize stem wood production [Lowell et al. 2014]. The values of sinuosity and leaning indices in both parcels are approximately equal. Poor form properties include loss of apical dominance, formation of numerous thick branches, angular kinking and distortions of branches, and twisted stems [Turvey et al. 1993]. The twisting of tree boles is influenced by both genetic and environmental conditions and is likely to occur for greater resistance against the wind. It is shown that spiral grain in the direction of the wind-induced torque improves the bending strength of the tree [Skatter and Kucera 1997].

In general, a low slenderness coefficient value (the ratio of total height to diameter at 1.3 m above ground) usually indicates a longer crown, a lower center of gravity, and a better developed root system. Therefore, trees with higher slenderness coefficient values (i.e., slender trees) are much more susceptible to wind damage [Wang et al. 1998] and snow damage [Tavankar et al. 2019a]. Tree species, genotype, age, competition, site (especially wind exposure), silvicultural treatment, and size and structure of the crown are all important factors in stem formation. Among all these factors, the crown, particularly crown length, plays a decisive role in determining stem form. The fact that torsion might be critical to the resistance of trees to wind provides an explanation for spiral grain growth [Skatter and Kucera 1997].

Non-destructive testing on standing trees may help to assess tree quality and can provide useful indications for silvicultural interventions [Russo et al. 2019].

Conclusions

The results of the present study show that selection cutting management has improved the quality and form of tree stems in a mixed beech forest. Selection cutting management has reduced the frequency of stem deformities. Decaying stems caused by logging damage account for a high percentage, and the need to adopt appropriate methods to reduce residual stand damage during forest operations is clear. A reduction in the frequency of stem deformity will make these valuable forest ecosystems more resistant to future changes and uncertain environmental conditions such as global warming, hurricanes, heavy rains, heavy snow and wind, pests, diseases and insects. The research revealed the importance of choosing trees for cutting. It is essential to consider the stem form of trees when marking them for silvicultural operations. Trees with deformed stems should be considered for cutting – of course, taking into account the diversity of species – to achieve economic goals, but giving consideration to the presence of thick and rotten trees for the ecological functions they perform in the forest. These aspects may require further investigation.

The main conclusions that can be drawn from this study are the following.

- Systematic and long-term stand monitoring and statistical quality control (SQC) are essential to follow the dynamics and ecological processes of forests.
- The regular use of non-destructive testing may help to assess the quality of forest trees.
- Silvicultural operations can have significant effects on the stem forms of trees and timber quality.
- The control of trees' competition for light in large logging gaps is important for reducing stem deformity.

- Selection cutting management can improve stem form and quality in high mixed beech forests.
- Pioneer species (maple and alder), due to their rapid growth, are more prone to sinuosity, leaning and bending deformities after selective logging operations.
- Differences between tree species can affect the frequency and type of stem deformity in high mixed beech forests.
- Damage to the residual stand during selection cutting operations should be minimized.

In addition to genetic and environmental factors, stand management is another important factor for tree bole quality.

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