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ORIGINAL PAPER

Wood quality and value production in mixed fir-spruce-beech stands: long-term research in the Western Carpathians

Rudolf Petráš[1], Julián Mecko[1]*, Michal Bošeľa[1,2], Vladimír Šebeň[1]

[1]*National Forest Centre - Forest Research Institute Zvolen, T. G. Masaryka 2175/22, SK – 960 92 Zvolen, Slovakia*
[2] *Faculty of Forestry, Technical University in Zvolen, T. G. Masaryka 24, SK – 960 53 Zvolen, Slovakia*

Abstract
Stem quality and damage was evaluated in mixed spruce-fir-beech stands. Moreover, an assortments structure was determined with their financial value. Results were compared with pure spruce (*Picea abies* [L.] Karst.), fir (*Abies alba* Mill.) and beech (*Fagus sylvatica* L.) stands. Repeated measurements on 31 long-term research plots, stand assortment models, assortment yield models and value yield models were used. Stem quality of fir and spruce was only slightly lower in mixed stands compared to pure stands but beech stem quality was considerably worse in mixed stands. Fir and spruce had slightly lower proportions of better IIIA quality logs and higher proportions of IIIB quality in mixed stands. Beech had worse assortment structure than spruce and fir, in general. Pure beech stands had higher proportions of better I–IIIA quality assortments than mixed stands by 1–7%. Fir and spruce average value production (€ m^{-3}) culminated at about 56 and 62 cm mean diameters. Almost the same value production was found in pure stands. In these stands it culminated at the mean diameter of 58 and 60 cm. Beech produced substantially less value on the same sites. In mixed stands, its value production culminated at the mean diameter of 40 cm. In pure stands, it culminated at the mean diameter of 36 cm. Although the production was found to be similar in both mixed and pure forests, higher damage intensity and less stem quality in mixed forests suggest that the pure forests can be more profitable.

Key words: silver fir; Norway spruce; European beech; mixed stands; assortments production

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1. Introduction

Mixed stands are usually expected to have higher production, which has repeatedly been proven (Pretzsch 2009; Forrester 2014). Mixed stands can be more productive than pure stands, however this depends on the site conditions, stand age and how the species interact.

A lot of mixed-stand studies quantify growth or yield of individual tree species by height or diameter growth (Künstle 1962; Monserud & Sterba 1996; Knoke et al. 2008; Petráš et al. 2014a), as well as by their production volume and increments (Kennel 1966; Prudič 1971; Míchal 1969; Hink 1972; Pretzsch 1992; Pretzsch & Schütze 2009; Lebourgeois et al. 2014; Petráš et al. 2014b). For Central Europe, these were mainly based on measurements on simultaneous plots in pure or mixed parts of the stand, and only few studies were based on long-term research plots in mixed stands. In the search for the causes of different growth and production in mixed stands, most authors focus on site, climate, tree species composition, the type of mixture and the stand age (Magin 1954; Kennel 1965, 1966; Hausser & Troeger 1967; Mitscherlich 1967; Hink 1972; Mettin 1985; Kramer et al. 1988; Pretzsch 2009; Pretzsch et al. 2010). Few authors provide detailed evaluation of the quality and value of wood produced in either pure forests (Karaszewski et al. 2013; Michalec et al. 2013) or mixed stands (Hausser & Troeger 1967; Kramer et al. 1988; Saha et al. 2012, 2014), and most of the above-mentioned authors agree that mixed stands have many advantages over pure stands, because the former more readily resist damage and have positive effects on soil properties. Mixed stands better utilize both above-ground and below-ground parts, especially when the tree species have different biological properties and requirements light, water and nutrient availability. These factors explain why higher wood production is expected in mixed stands than in pure on some sites.

Knowledge on wood quality especially that of mixed-species stands, are essential for decision making in forestry. There is not only financial interest, but also in carbon management such as different wood products store carbon for different time periods. There is, however, a lack of knowledge on wood quality and value in mixed forests (Saha et al. 2012, 2014; Štefančík & Bošeľa 2014). Therefore, our aim is to fill the knowledge gap and go beyond the traditional quantitative production research by assessing assortment structure of mixed forests in Central Europe. We quantify differences in wood quality and financial yield between mono-specific and mixed-species forests. We also present an integrated methodological concept based on long-term experimental data and integrated models of wood quality and yield production.

The study particularly aims (i) to evaluate stem quality and damage in mixed forests in the Western Carpathians; (ii) to determine their assortment structures and financial value; and (iii) to compare results between mixed and single species forests of Norway spruce (*Picea abies* L. Karst), silver fir (*Abies alba* Mill.) and common beech (*Fagus sylvatica* L.)

Corresponding author. Michal Bošeľa, e-mail: ybosela@tuzvo.sk, phone: +420 5206 310

in similar growth conditions. We hypothesise that, although the quantitative production is supposed to be higher in mixed forests, species-pure forests might produce higher value production because less-quality wood is expected to be produced.

2. Material and methods

2.1 Research plots

Empirical material included repeated measurements from 31 long-term research plots (LTPs). These plots were established in the Western Carpathians (Fig. 1) in the 1960's and 1970's to study the growth and production of pure and mixed forest stands (Table 1). The plots were situated in the western and eastern parts of the Slovenské Rudohorie Mountains; the western parts in the Hriňová region and the eastern ones in the Spiš and Hnilecká dolina valley. The altitude ranged between 480 and 970 m a.s.l. The prevailing climatic-geographic subtype is a cold mountain climate, which gradually changes to mild and slightly warm mountain climate (Lapin et al. 2002). Plots were established in and represent the following forest types: beech-fir fertile forests; fir-beech forests on eutrophic to moderately oligotrophic soils; beech-fir forests with spruce on oligotrophic soils and beech-fir forests with sessile oak (*Quercus petraea* Matt.) on oligotrophic soils. The tree species mixture differed between LTP; with all three species being present on 16 LTPs; spruce with fir on 13 LTPs; and fir with beech and spruce with beech each on one LTP. Fir had the highest proportion on the LTPs, followed by spruce, and then beech. Stand age at the time of LTP establishment varied from 32 to 159 years. All research plots were repeatedly measured and tended with negative thinning from below; most often at regular 5-year intervals. The same thinning method was applied in all the LTPs; both established in mixed and pure forests. The majority of the plots were measured four to eight times. The rectangle-shaped LTP area ranged from 0.2 to 1 ha, with all trees numbered and the place of diameter measurement marked. The height of all trees in the plots was only measured at the first and last measurements, while a sample of trees were selected for height measurement throughout the entire period. These sample trees were selected from the entire DBH range to enable developing the height-diameter model. The model was then used to estimate the height of the all remaining trees.

2.2. Assessment of stem quality and damage

Using the Kraft classification system (Kraft, 1884) (predominant, dominant, co-dominant, intermediate, suppressed/overtopped), trees were classified into 1–5 tree classes (, and their stem quality and damage were assessed. Stem quality was determined in the following three classes at each inventory prior to 1990: (1) best quality stems, straight and without technical defects; (2) average-quality stems with small technical defects and (3) lowest quality stems with large technical defects. This grading had been applied without consideration of the timber end-use, and more appropriate stem-quality classification was introduced in 1991 as new assortment models were developed in Slovakia (Petráš & Nociar 1991). Stems were then categorized in A (High quality stems, almost without knots (only healthy knots under 1 cm in diameter at the base), twisting (spiral growing), and without other technical defects.), B (Average quality stems, with small technical defects. In the case of hardwood species all of the healthy or unhealthy knots with diameters under 4 cm are allowed. For spruce and fir healthy or unhealthy knots under 4 cm and for

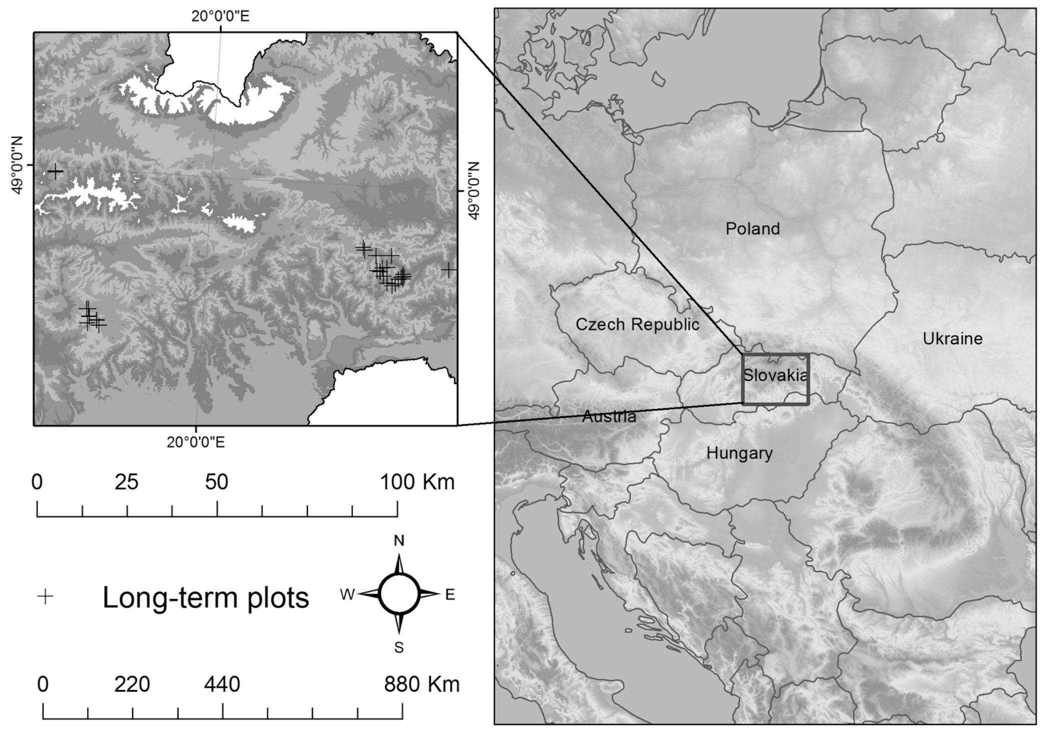

Fig. 1. Location of study sites in the Western Carpathians.

Table 1. Basic information on surveyed LTPs: t_0 is the age at plot establishment, t_n is the age at last measurement and G denotes stand basal area.

LTP	Area [ha]	Altitude [m]	Proportion [% of G]			Site index [1 m]			Age	
			fir	spruce	beech	fir	spruce	beech	t_0	t_n
15	0.40	480	81.5	6.3	12.2	31	32	27	65	108
44	0.36	760	68.3	4.2	27.5	30	28	30	77	120
45	0.49	730	65.1	16.6	18.3	35	36	30	82	123
46	0.49	560	94.1	5.9		29	29		104	145
47	0.48	650	84.0	10.7	5.3	30	32	21	94	135
50	1.00	724	69.2		30.8	27		23	159	202
51	0.30	588	92.3	7.7		31	33		47	88
52	0.43	775	81.7	9.5	8.8	22	23	16	141	185
53	0.66	865	82.9	17.1		30	32		110	152
54	0.28	740	77.4	22.6		31	31		52	93
56	0.49	968	92.4	7.6		29	31		121	162
60	0.44	885	12.5	87.5		33	33		73	114
61	0.65	890	7.2	89.3	3.5	32	33	29	83	124
63	1.00	686	63.8	31.3	4.9	26	26	19	140	184
79	0.24	600	89.6	10.4		31	32		53	96
80	0.42	900	66.5	23.7	9.8	29	30	24	74	114
81	0.40	640	91.1	8.9		31	31		47	88
82	0.30	690	84.8	15.2		35	37		32	73
83	0.20	790	94.4	5.6		30	37		36	79
89	0.23	630	83.6	16.4		29	33		40	80
91	0.67	700	64.5	15.1	20.4	31	32	27	88	124
93	0.56	560	40.1	9.2	50.7	27	26	25	80	122
94	0.64	770	33.0	47.8	19.2	29	32	29	81	111
107	1.00	717	83.4	7.8	8.8	34	38	17	142	181
110	0.81	820	90.7	9.3		34	35		140	166
111	0.49	670		70.0	30.0		38	32	69	110
112	1.00	839	18.0	36.8	45.2	37	39	28	95	134
114	0.96	770	61.0	5.7	33.3	36	39	27	103	144
115	0.60	818	9.9	69.5	20.6	38	38	27	89	115
118	0.35	705	45.3	52.2	2.5	34	34	14	99	125
119	0.54	705	31.5	68.5		36	39		95	136

Note: G – stand basal area, t_0 – age at establishment, t_n – age at the last measurement.

Scots pine less than 6 cm are allowed.), C (Low quality stems with large technical defects, with high frequency of branches (densely branched trees), twisting up to 4% of straight length axis. Healthy knots without limit for the size (diameter) are allowed, unhealthy knots up to a diameter of 6 cm in the case of softwood species, and up to 8 cm for hardwood species.) and D (Poor quality stems with unhealthy knots over 6 cm for softwood species and over 8 cm for hardwood species, which are also affected by rot. The stems are only utilized as fuelwood.) classes, dependent on quality assessment of their lower third portion. For this study, the new classification was only used in order not to affect results and interpretations.

Damaged stems (visually assessed on standing trees) significantly predict inside-wood defects such as rot, and the red heart often found in beech trees. Therefore buttress and surface roots were evaluated in addition to surface stem damage; with damage presence only recorded, disregarding its size, intensity and position.

The proportions of A–D classes and damaged stems were calculated for each inventory after 1990; with average percentages and standard deviations determined for each tree species. The same variables were calculated for pure fir, spruce and beech stands by assortment yield models (Petráš & Mecko 1995; Petráš et al. 1996). The proportion of the *A–D* stem quality classes is a function of q site index (Equation 1). Here, site index is the mean stand height at 100 years standard age, derived from height growth models developed for Slovakian yield models (Halaj & Petráš 1998). The proportion of damaged stems, $p\%$, is a function of stand age t.

$$A, B, C, D\% = f(q) \qquad [1] \qquad\qquad p\% = f(t) \qquad [2]$$

As follows from the models the stands with higher site index produce a higher proportion of better quality stems, and the proportion of damaged stems increases with the stand age.

2.3. Estimation of assortment structure

Assortment structure was estimated for each LTP and tree species using stand assortment models (Petráš & Nociar 1991; Petráš 1992). These models provide assortment proportions $S\%$ for each tree species as a function of the following factors: mean diameter d_v; proportion of stem quality classes $kv\%$; proportion of damaged stems $p\%$; and for beech trees also as a function of stand age t.

$$S\% = f(dv, kv\%, p\%, t) \qquad [3]$$

Individual assortments represent log classes based on log quality and diameter. The proportion of the following classes results from Equation 3:

Class	*End-use*
I	cut veneer, special sports and technical equipment,
II	plywood, matches and sports equipment,
III(A, B)	saw logs (better quality – IIIA, worse quality – IIIB), building timber and sleepers,
V	pulpwood, chemical and mechanical processing for cellulose and wood-based panels production,
VI	fuel-wood.

I–IIIB classes are split into 1–6+ diameter classes in the stand assortment model.

The assortment structure of fir, spruce and beech single species stands was derived from assortment yield models (Petráš & Mecko 1995; Petráš et al. 1996), where assortment proportions $S\%$ is a function of stand age t and site index q.

2.4 Defining the assortments value

Assortment value was calculated as the product of assortments volume and wood prices for each log quality and diameter class (Fig. 2). Wood prices were taken from the price list published by Slovak state forest enterprise in 2013.

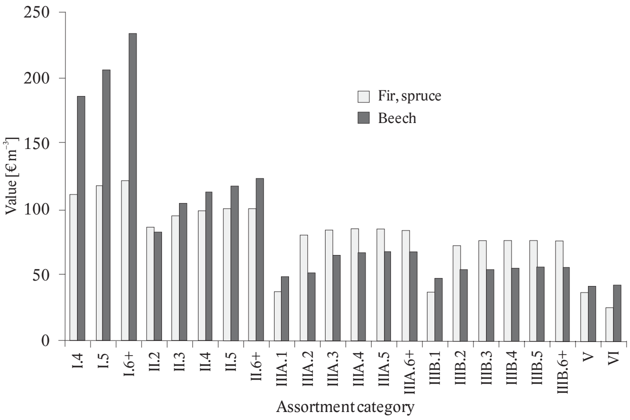

Fig. 2. Wood prices (€ m^{-3}) by I–VI qualitative classes, and by 1–6+ diameter classes of fir, spruce and beech.

Structure and production value were calculated in the following two variants to evaluate the mixed stand production. These variants were chosen with regard to input data source for each variant:

Variant	*Source of input data (stem quality and damage, mean diameter)*
1	All input data emanates from LTP measurements.
2	All input data comes from the models developed for pure stands.

3. Results

3.1. Stem quality and damage

The proportions of stem quality classes on LTPs in mixed stands indicate that B class dominates in fir and spruce with 62 to 66% (Fig. 3). The beech stem quality decreased during the study period and the highest proportion of approximately 57% was found in class C. This percentage was higher than both the average quality B class and the highest quality A class. In addition, the 2% of poor quality D class increased overall worst quality of beech in the mixed stands. Standard deviations suggested that fir had the lowest between-plot variability in the all quality classes, followed by spruce, with the highest variability in beech. The coefficients of variation for their most represented B class were 11% for fir and 26% for spruce, with 30% for C class beech.

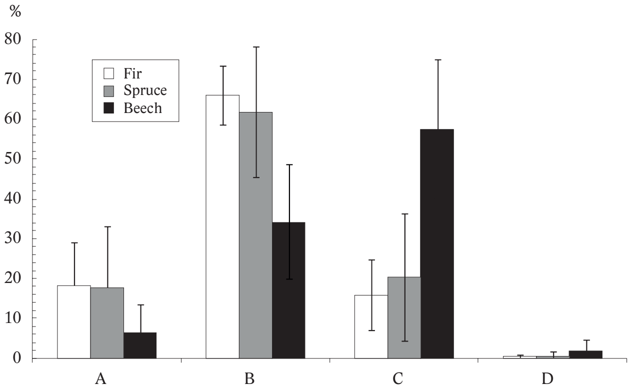

Fig. 3. Proportion of A–D stem quality classes by tree species in mixed stands. The whiskers denots 95% confidence intervals.

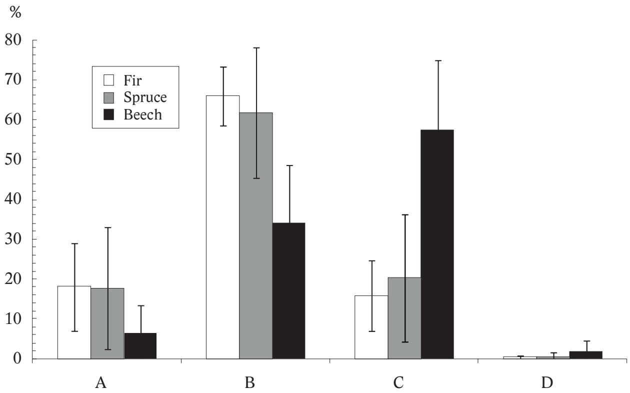

Fig. 4. Differences in A-D stem quality classes between mixed and pure stands.

In comparison to the quality of pure stands growing on the same sites (Fig. 4), fir and spruce had higher proportions of both best A stem quality class by 4–5% and C class by 9–13%. In contrast, the proportion of average B quality class was lower by 14–17%. In addition, beech had 24% less best A quality class stems in mixed than pure stands as well as 13% less B class quality. This 37% sum leaves higher proportions of poor quality C class stems. We can clearly conclude that conifers in mixed stands produced more stems of both best and worst quality than pure stands, and the average-quality stems diminished. In contrast, the opposite was found for beech. Beech mixed with fir and spruce had a lower proportion of average quality stems by 13%, but the proportion of the best quality stems was even 24% lower compared to pure beech forests.

Stem damage (e.g. after logging, debarking by a deer species, etc.) substantially reduces the wood quality. The proportion of damaged stems was between 49 and 53% for all the LTPs and all the tree species (Fig. 5). In the pure stands (as simulated by the models) the proportions were different. Spruce had the highest proportion of damaged stems (61%), followed by fir (46%) and beech (23%).

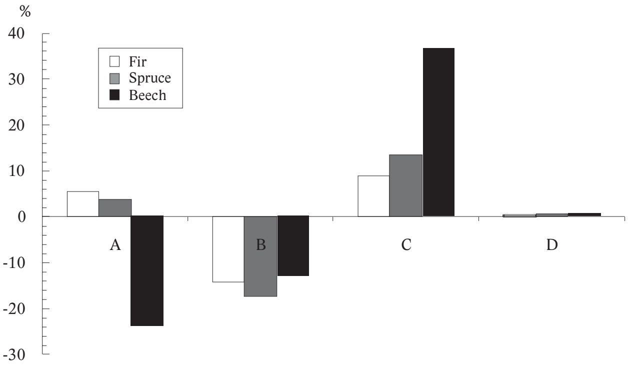

Fig. 5. Damaged stem proportions in mixed and pure stands.

3.2. Assortment structure

Fir and spruce exhibited very similar assortment structure, where IIIA and IIIB saw-log classes prevailed with 30–50% (Fig. 6). These were followed by pulpwood assortments in V class with 10–15% and the most valuable assortments of I and II class with 3–5% and then fuel-wood amounting approximately to 1%. Differences in assortment structure between the variants are far smaller. For both species, the proportions of the highest quality assortments (I and II) in mixed forests (1st variant) were only a few tenths of percent higher than in pure stands (2nd variant). Saw logs, however, had contrasting proportions. Mixed stands had a slightly lower proportion of IIIA assortment and higher proportion of worse quality IIIB assortment than pure stands.

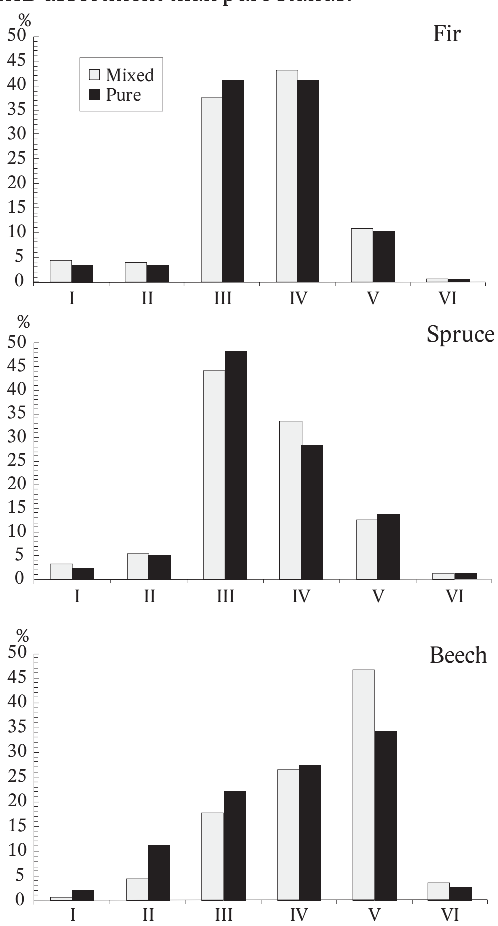

Fig. 6. Volume proportions of I–VI quality class logs in mixed and pure fir, spruce and beech stands.

The assortment structure of beech is worse than that of both spruce and fir. While timber volumes increased steadily between I and V assortment category, pure stands had simultaneously higher proportions of better quality assortments (I–IIIA category) than mixed stands by approximately 1–7%, but this situation was reversed for lower quality IIIB–VI classes.

3.3. Assortment and value production

Value of assortment and timber production is additionally influenced by actual prices. We found the proportions of the assortments of I–IIIA class calculated from the prices (Fig. 7) were higher than the proportions derived from their volumes (Fig. 6). Fir was found to have a higher proportion by 1–3%, spruce by 2–5% and beech by 2–8%. In contrast, lower proportions were found for IIIB–VI assortment classes; fir by 1–5%, spruce by 1–7% and beech by 1–10%.

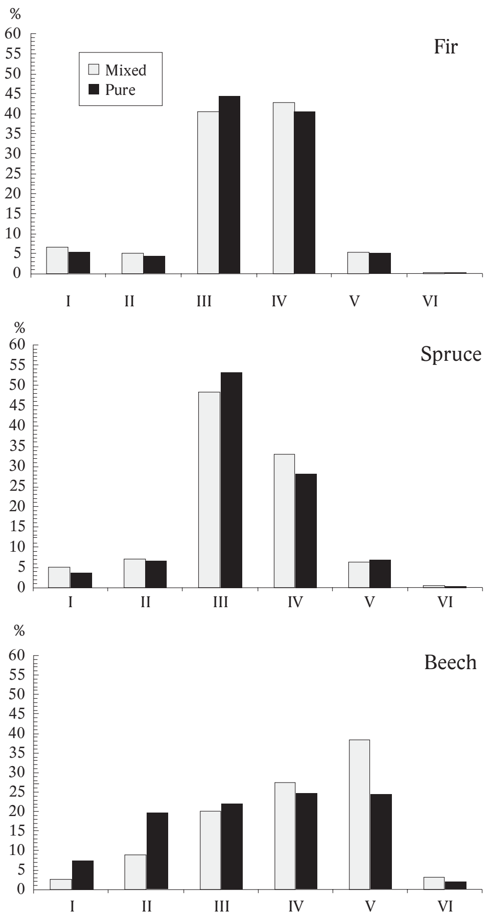

Fig. 7. Value proportions of I–VI quality classes logs in mixed and pure fir, spruce and beech stands.

The value of wood production in mixed forests is not only influenced by assortment structure and prices, but also by the different timber volume of individual tree species. The average production value (€ m^{-3}) was calculated for each tree species and each variant to compare tree species production (Fig. 8, 9), and these were assessed as a function of mean diameter and site index. The value production pattern of fir and spruce followed a very similar course and culminated at

56 and 62 cm in mixed stands, at approximately 79 € m^{-3}. Simulations by the Slovakian yield models showed almost the same production in pure stands, where it culminated at mean diameters of 58 and 60 cm with approximately 79 and 78 € m^{-3}. These values approximate both their culmination and mean diameter range. In contrast, beech produced significantly less on the same site index; where mixed stand production culminated at 40 cm mean diameter and just below 54 € m^{-3}. It culminated earlier in pure stands at 36 cm mean diameter and by 10 € m^{-3} higher value.

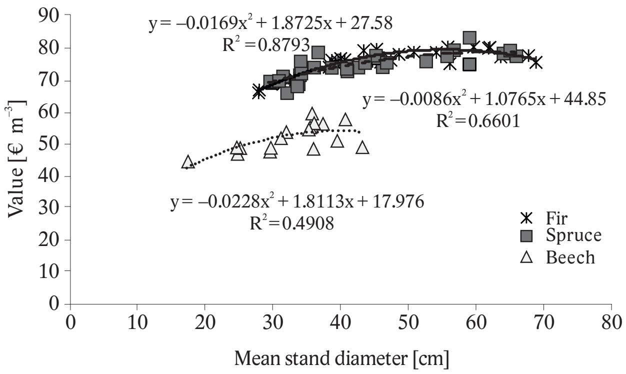

Fig. 8. Average value of fir, spruce and beech wood (€ m^{-3}) produced in mixed stands.

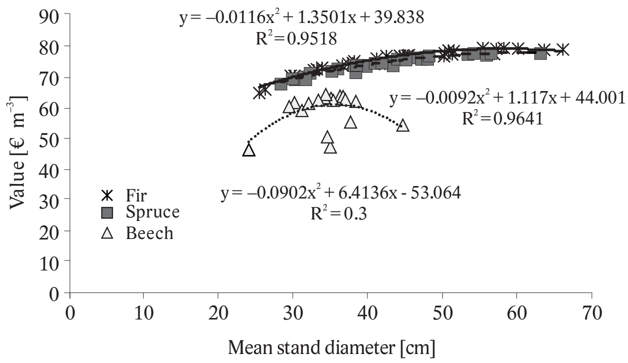

Fig. 9. Average value of fir, spruce and beech timber (€ m^{-3}) produced in pure stands.

4. Discussion

Spruce, fir and beech are ecologically and economically the most important tree species in the Western Carpathians and these naturally form both pure and mixed stands.

Our results indicated slightly worse stem quality in mixed forests for all the species. Wiedemann (1951) suggested this was due to vertical and horizontal structure of mixed forests where less dense crown canopy enables longer survival and consequent branch roughening than in pure stands with their more concentrated single-layer canopy. Furthermore, strong heliotropism negatively influences beech lengthwise and crosswise shape and also its spiral grain (Krammer et al. 1988; Pretzsch & Schütze 2009). Mechanical stem damage introduces a secondary factor; caused mainly by inappropriate technology in logging and by red deer bark-stripping and peeling. Beech stems generally have harder wood, but stem damage increases the probability of red heart (Petráš 1996a, b). Although overall stem damage was higher in pure stands, our results highlight that fir and especially beech suffered less damage in pure than in the mixed stands compared to spruce which had a higher damage in pure forests. This was probably because bark of spruce is one of the natural food sources in winter (Finďo & Petráš 2011).

Stem quality and damage is reflected in assortment structure. Fir and spruce had very similar assortment proportions in both mixed and pure stands. Thicker stem branches in mixed stands led to a slightly lower proportion of higher quality IIIA class logs and a higher proportion of IIIB. However, beech reached essentially lower timber quality in mixed forests. Wiedemann (1951) and Krammer et al. (1988) also suggested that beech usually has higher potential for best quality assortment in pure stands than in mixed. For this reason, Wiedemann (1951) and Prudič (1971) suggested that maximum beech proportion in mixed stands is usually limited to 20–30%.

Financial values comprehensively reflected the production capabilities of these stands. Our results confirmed that fir and spruce are the major value producers in mixed stands, with beech significantly lagging in this respect (Wiedemann 1951; Prudič 1971) and also performing worse in pure stands. Hauser & Troeger (1967) reported that fir produces 9% greater value than spruce in mixed spruce-fir stands because of their greater diameter. Here, it is important to realize that assortment tables do not consider stem quality and damage; these rely solely on dimensions for production value calculation.

5. Conclusions

This study suggested that conifers had only slightly worse stem quality in mixed than pure stands. However, beech had considerably lower stem quality in mixed forests While the proportion of damaged stems in mixed stands was high for all the tree species, fir and especially beech stems experienced less damage in pure stands. Spruce trees, in contrast, suffered higher damage in pure stands In mixed forests, beech was found to have overall worse assortment structure than spruce and fir.

This study suggested that wood quality and assortment structure was considerably lower in mixed forests only for beech, while almost no differences were found for conifers. This thus encourage forestry practice to prefer mixed-species forests, especially when static stability and resistance to climate change should be taken into account.

Acknowledgements

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