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Growth and Timber Quality of European Larch Planted in Areas Reclaimed After Coal Mining in Central Poland

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Abstract

*Understanding the impact of reclamation measures on the quality of timber produced in post-mining areas is crucial for the proper establishment of future forest cultures on such sites. We studied European larch trees (*Larix decidua* Mill.) grown since 1981 on the external dump of a brown coal mine in Bełchatów (Central Poland). In particular, the effects of stand admixture and the intensity of mineral fertilization, applied in the initial phase of tree growth, on the increments and quality of larch wood were evaluated. Total tree height and stem diameter of 4-meter sections were measured. Qualitative timber classification took into account the share of wood defects, which excluded the timber from a higher quality-dimensional class. Larch trees grown in a monoculture had a better quality of wood compared to larch grown mixed with other species. Fertilization, applied in the initial afforestation period, had only a limited effect on the growth of larch trees. Curvature and knots determined timber quality most significantly. While knots had a decisive importance in larch growing in the monoculture stands, curvature determined wood quality in the admixed larch stands.*

Keywords: wood defects, fertilization, monoculture, mixed stand

1. Introduction

Open-pit mining techniques for coal and other materials have the consequence of interfering with the natural environment. According to the majority of international regulations, all areas of former open-pit mining need to undergo land reclamation, most of which is ultimately reclaimed for forestry (Pietrzykowski and Krzaklewski 2007). The predominance of forest reclamation in the rehabilitation of former opencast mining facilities results from the particular way these facilities were structured. Most of the dump sites were built in a non-selective manner, which led to a large diversity of the deposited rocks of the overburden in the surface layer of the dump, both horizontally and vertically. Moreover, among the stored rocks, sandy formations are very often dominant, characterized by a low content of basic macronutrients as well as low sorption and retention abilities (Heinsdorf 1996). Furthermore, it was rare that such substrates were covered with peat or fertile layers, due to the high costs of such treatments. In Poland, for instance, forest reclamation is carried out in about 50% of the areas degraded by mining activities (Krzaklewski 2017). According to Pietrzykowski et al. (2015), previous agricultural and forest areas occupied by mining and industry are estimated at approx. 45,000 ha in Poland, and approximately 25,000 ha of this area is then reclaimed for forest purposes.

Reclamation is not limited to restoring the use-value of degraded soils but includes a whole range of activities aimed at restoring the entire landscape. From an ecological point of view, the main goal of reclamation is to restore the ecosystem at the reclaimed post-mining facility (Bradshaw and Hüttl 2001, Krzaklewski 2017). Therefore, the main goal of rehabilitation in post-mining facilities is to restore soil as the basic element of the terrestrial ecosystem (Hüttl and Bradshaw 2000, Frouz et al. 2013). The methods of soil reconstruction can be subdivided into: technical methods, in which the entire soil profile is restored by topsoiling using organic and organic-mineral horizons previously removed from areas occupied by mining; and biological methods, consisting in the introduction of plant biomass through green fertilizers (Pietrzykowski et al. 2017). In the case of the biological method, soil preparation before introducing trees to the reclaimed area consists only in the appropriate shaping of the terrain and the implementation of suitable fertilization treatments. The species of trees introduced most frequently as part of the forest reclamation process include pioneering species such as: black alder, silver birch, Scots pine, and aspen (Krzaklewski 2017). As part of reclamation activities performed at former mining facilities, tree species are introduced to post-mining habitats that are characterized by various physico-chemical properties of the newly created soil in relation to the soils of natural habitats (Pietrzykowski and Socha 2011). Trees always fiercely compete for nutrients and water resources; however, in post-mining sites, where basic macronutrients (C, N and P) are often lacking and water resources are limited, this competition often leads to generating varying forms of trees and different timber quality compared to the form and timber quality of trees growing in managed forests (Ochał et al. 2010, Pająk et al. 2016, 2019, 2021).

The Bełchatów Brown Coal Mine is one of the largest open-pit mines in Europe. Its annual output reaches approx. 40 million tonnes of brown coal, most of which is used to produce electricity (Kasztelewicz et al. 2018). It is predicted that about 5000 ha of areas exploited by the Bełchatów mine will ultimately have to undergo reclamation for forest purposes (Krzaklewski 2017). The first afforestation tasks on the northern slope of the external dump of the Bełchatów Mine were carried out in the years 1978–1981 (Pająk and Krzaklewski 2007). Thus, the earliest parts of the external dump reclaimed for forest purposes include approx. 40-year-old stands. Hence, it seems reasonable to assess the quality and dimensions of the timber that grows there.

This study aims to determine the quality of the timber of European larch introduced in pure and mixed stands as a part of forest reclamation on the external

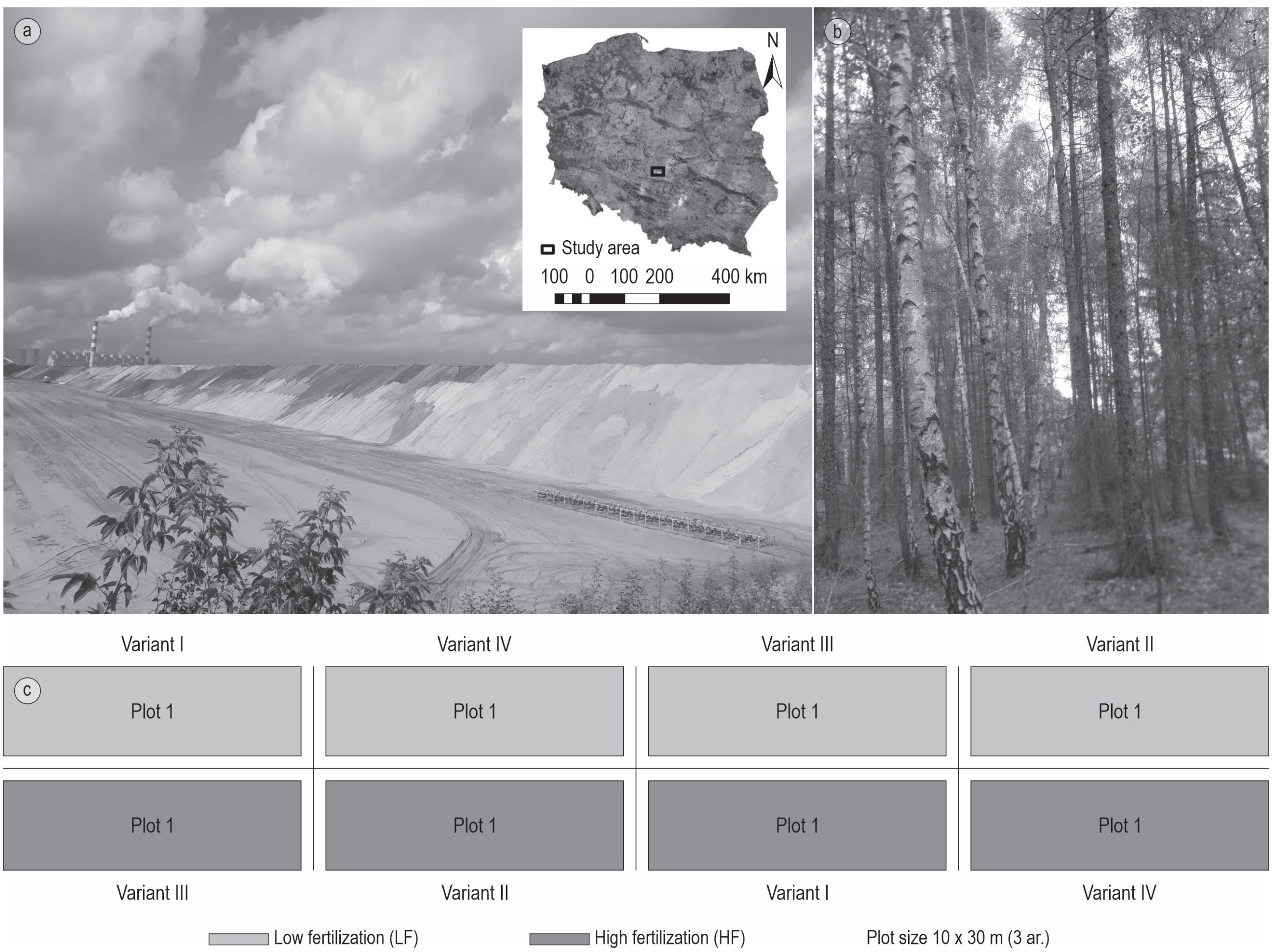

Fig. 1 (A) Photograph of lignite mining area in Bełchatów with an embedded general map of area location in Poland; (B) photograph of typical plant cover in study site, a reclaimed area with mature larch trees; (C) schema of the entire experiment

dump of the Bełchatów Mine. Specifically, the effects of species composition of the forest cultures and the intensity of fertilization applied as a part of reclamation measures are evaluated.

2. Materials and Methods

The research area is located in the central part of Poland, in the Łódź Voivodeship (province), in the external dump of the Bełchatów Mine (51°13' N, 19°24' E). The research plots were set up in 1981 on the northern slope of the external dump of the Bełchatów Field. The plots were established on a ledge separating the 3rd and 4th tipping levels, on overburden substrates (sands, quaternary clays and loams) differentiated in the soil-forming layer. During the establishment of the research plot, soil conditions were examined, and found to be similar but not uniform over the entire plot. In the top layer (0–20 cm), there were rocks with a mechanical composition of loose sand and light loamy sand. Below (20–50 cm), there were deposits composed of heavy clay sand or sandy loam. In turn, deposits below 50 cm were dominated by medium-compact formations with a light clay composition. The rocks deposited on the research plot were characterized by a pH value (H_2O) in the range between 7.7 and 8.8, as well as an insufficient content of nitrogen (0.01–0.02%) and phosphorus (5.4–0.6 mg/100g P_2O_5) (Krzaklewski et al. 1981, Pająk 2017). Taking into account the origin of the substrate and the characteristics of the soils formed, based on the WRB classification (IUSS WRB Working Group 2015), the soils on the experimental plot can now be classified as Spolic Technosols (Arenic, Ochric, Transportic).

In total, eight experimental plots (10x30 m; 0.03 ha) were established. The entire experiment was divided into two blocks, northern and southern, with treatments differing in the intensity of fertilization applied beginning in 1983 as part of reclamation treatments at the beginning of afforestation, as well as being planted with different tree species admixtures in 1981. In spring 1983, half of the plots were fertilized with mineral NPK (93 kg/ha of total N, 120 kg/ha of K_2O and 115 kg/ha of P_2O_5), while the second half was left without fertilization. In both of the next two years, all plots were fertilized: 100 kg/ha of total N, 43 kg/ha of K_2O and 30 kg/ha of P_2O_5 in 1984 and 97 kg/ha of total N, 25 kg/ha of K_2O and 12 kg/ha P_2O_5 in 1985 (Pająk 2017). The fertilization at the initial stage of forest reclamation was performed in order to check the adaptation and growth of the introduced species to the raw soil of the external dump site (Krzaklewski et al. 1981).

Table 1 Species composition and number of seedlings per plot. Variant I refers to larch monoculture plots, variants II–IV refer to mixed stands

Variant	Plot number	Species	Species composition, %	Number of seedlings pcs per plot
I	1LF, 6HF	European larch (*Larix decidua* Mill.)	100	200
II	4HF, 7LF	European larch (*Larix decidua* Mill.)	40	80
		Common birch (*Betula pendula* Roth)	30	60
		Douglas fir (*Pseudotsuga menziesii* var. *menziesii* Franco)	30	60
III	2HF, 5LF	European larch (*Larix decidua* Mill.)	40	80
		Black locust (*Robinia pseudoacacia* L.)	35	70
		European beech (*Fagus sylvatica* L.)	25	50
IV	3LF, 8HF	European larch (*Larix decidua* Mill.)	40	80
		Black alder (*Alnus glutinosa* (L.) Gaertn.)	35	70
		Common oak (*Quercus robur* L.)	25	50

Notes: LF – low fertilization; HF – high fertilization

Accordingly, as shown in Fig. 1, research plots #1, #3, #5 and #7 (LF) received lower rates of fertilization than plots #2, #4, #6 and #8, receiving high fertilization (HF).

The trees were planted in 4 variants (I – monoculture; II, III and IV – mixed stands; see Fig. 1). The percentage share of seedlings, the number of seedlings per plot, and the proportion of species in the admixtures are presented in Table 1.

In spring 1981, 3-year-old European larch seedlings were planted in the 1x1.5 m spacing separately or in an admixture with other species. See Table 1 for details. Due to a frost event, Douglas fir was eliminated (plots #4 and #7) and was replaced with 3-year-old larch seedlings in 1983 (Pająk 2017).

In summer 2019, the following tasks and measurements were performed on all plots:

- ⇒ all trees were inventoried
- ⇒ the height of larch trees was measured with a SUNNTO altimeter (Espoo, Finland) (exact to 0.5 m)
- ⇒ diameter at breast height (DBH) of all larches at least 7 cm thick at a height of 1.3 m were measured
- ⇒ over a 4-meter section of the trunk butt, each tree was subjected to timber quality classification based on technical conditions for large-sized coniferous wood (Technical Conditions 2019).

Moreover, the timber classification took into account the share of wood defects which excluded the timber of a higher quality-dimensional class (Technical Conditions 2019).

The calculation of the volume of 4-meter trunk sections was performed using appropriate volume tables (Czuraj 1991). Between-treatment differences for data with a normal distribution were tested with a *t*-test, while data that did not show a normal distribution were analyzed using the Mann–Whitney *U*, Kruskal-Wallis and multiple comparison post hoc tests.

3. Results

After almost 40 years of growth on the external dump, the European larch trees had an average height of 14.8 m. Larch trees growing in the monoculture had a slightly higher average height (14.9 m) than larches growing in mixed stands (14.7 m). This difference was statistically significant, as confirmed by the Mann–Whitney *U* test (Z=4.30; p=0.00). Considering individual plots, it can be seen that the single-species stands (variant I) contained both the tallest (LF plots) as well as the shortest (HF plots) trees (Table 2). However, the lowest mean larch height (12.9 m on average) was observed in variant II (mixed with birch, where some larches were introduced 2 years later). The mean height was 15.7 m in both variant III (mixed with locust and beech) and variant IV (mixed with alder and oak). The multiple comparison post hoc test showed significant differences between the heights of trees from variants I (monoculture) and II (mixed with birch) (p=0.00) as well as between I (monoculture) and III (mixed with locust and beech) (p=0.01) (Table 3). It was also noted that the average height of larch trees from the LF plots was higher (16.1 m) than that from the HF plots (13.5 m). The Mann-Whitney *U* test showed significant differences in the height of larch trees between the high and low fertilized plots (Z=4.14; p=0.00). The tallest larch trees (19 m on average) were found when planted in monoculture on less fertilized soil (1LF plot). Noticeably, the tree height had the greatest diversity in 6HF (high fertilized monoculture), where the coefficient of variation was about 32%.

The average overall DBH value of the larch trees was 18.6 cm. Similar to height, trees growing in the monoculture (variant I) showed a greater average DBH (19.2 cm) than trees growing in mixed stands (variants II, III and IV) (18.4 cm) (Table 4). The applied *t*-test showed significant differences between the data groups described above (t=4.68; p=0.00). Taking into account the species composition of the established stands,

Table 2 Mean height, standard deviation and coefficient of variation of larch trees in each plot

	Monoculture		Mixed stands					
Variant	I		II		III		IV	
Plot number	1LF	6HF	4HF	7LF	2HF	5LF	3LF	8HF
Number of trees, N	35	16	33	25	19	16	33	20
Average, m	19.0	10.7	11.4	14.3	17.1	14.2	16.7	14.7
Standard deviation, m	0.61	3.42	2.66	0.76	2.83	2.06	3.44	3.34
Coefficient of variation, %	3.21	31.96	23.33	5.31	16.55	14.51	20.60	22.72

Notes: LF – low fertilization, HF – high fertilization

Table 3 Post-hoc test results for tree height (*p* value)

Variant	I	II	III	IV
I	–	–	–	–
II	0.00*	–	–	–
III	0.01*	1.00	–	–
IV	0.06	0.39	1.00	–

Notes: * – statistically significant differences

it was found that the lowest average DBH occurred in variant II (mixed with birch; 16.1 cm), slightly higher in variant III (mixed with locust and beech; 18.8 cm), and the highest in variant IV (mixed with alder and oak; 20.3 cm). The *t*-test showed no significant differences in the DBH of larch trees from variants I (monoculture) and III (mixed with locust and beech) (t=1.16; p=0.25) as well as III (mixed with locust and beech) and IV (mixed with alder and oak) (t=1.04; p=0.30) (Table 5). There were statistically significant differences between the remaining admixture variants.

Larch trees growing on the LF plots had a greater average DBH (19.9 cm on average) than those growing on HF plots (17.3 cm on average). Larch trees from the 1LF plot had the highest DBH (23.8 cm on average), while the lowest DBH was found in plot 4HF (mixed with birch; 13.1 cm on average). Nevertheless, the *t*-test did not reveal any significant differences in DBH values of larch trees from the LF and HF plots (t=1.82; p=0.07) when averaged across all mixing ratios.

The overall average volume of the 4-meter butt sections of the larch trees per plot (0.24 ha) was 103.84 m^3, i.e. 432.67 m^3 per hectare. Considering the volume of the larch trees growing in the different admixtures separately, larch trees in variants III (mixed with locust and beech; 64 m^3/ha) and IV (mixed with alder and oak; 65.5 m^3/ha) show the highest stand volume, followed by larch trees growing in the monoculture (variant I; 62 m^3/ha). The smallest volume of 4-meter butt sections was noted in variant II (mixed with birch; 24.85 m^3/ha).

Table 4 Mean breast height diameter, standard deviation and coefficient of variation of larch trees in each plot

	Monoculture		Mixed stands					
Variant	I		II		III		IV	
Plot number	1LF	6HF	4HF	7LF	2HF	5LF	3LF	8HF
Number of trees, N	35	16	33	25	19	16	33	20
Average, cm	23.8	14.6	13.1	19.0	18.4	19.2	17.5	23.0
Standard deviation, cm	2.53	5.13	3.64	3.67	5.87	4.80	4.13	6.85
Coefficient of variation, %	10.63	35.14	27.79	19.32	31.90	25.00	23.60	29.78

Notes: LF – low fertilization, HF – high fertilization

Table 5 Results of *t*-test for tree DBH

Variant	*t*	*df*	*p*
I–II*	4.95	107	0.00
I–III	1.16	64	0.25
I–IV*	3.21	102	0.00
II–III*	–2.28	71	0.02
II–IV*	–2.16	109	0.03
III–IV	1.04	66	0.30

Notes: * – statistically significant differences

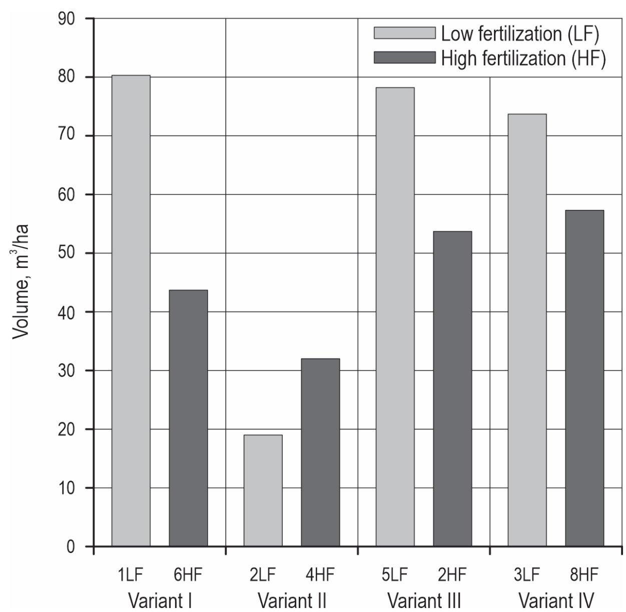

Fig. 2 Volume of 4-meter-long butt sections of larch trunks per hectare in individual plots. Variant I refers to larch monoculture plots, variants II–IV refer to mixed stands (see Table 1 for details)

In terms of fertilization, it was noted that larches growing on the LF plots had higher timber volume (247.30 m^3/ha), while the volume of larch trees growing on the HF plots was only 185.40 m^3/ha. The larch trees in plot 1LF had the highest volume of 4-meter butt sections (80.30 m^3/ha) as compared to other treatments investigated. On the contrary, the lowest volume was recorded in plot 7LF (mixed with birch, where some larches were introduced 2 years later), only 19.0 m^3/ha (Fig. 2).

The larch trees in the experiment had a significant share of wood in quality-dimensional class WD (Technical conditions 2019), i.e. large-sized low-quality round timber for general use (64%). Large-sized medium-quality round timber for general use (classified as WC) amounted to 33%. A minor part (1%) of the larch timber was classified as class WB (i.e. higher quality than WC).

Analyzing the effect of admixture plantings, the best quality of wood was found in larch trees growing in the monoculture (variant I): 57.6% classified in WC and 42.4% in the WD category. Whereas 26.5% and 73% of larch trees growing mixed with other species were classified as WC and WD category, respectively. Considering the admixture variants in detail, the lowest quality of larch wood was found in variant II (mixed with birch), where only 13.5% of timber was classified in the WC category.

Further analysis revealed the substantial influence of the rate of fertilization on timber quality. Higher fertilization rates led to a reduced wood quality (i.e. an enhanced representation of WD category) on most of the experimental plots (Fig. 3). The best quality was noted in larch growing in plot 1LF (LF, monoculture) due to the significant dominance of class WC (93.4%). On the contrary, all larch trees were classified as WD in the 4HF plot.

Stem curvature (46% one-side curvature and 24% multilateral curvature) had the greatest impact on timber classification, while knots had a smaller influence, amounting to just 30%.

It was found, however, that larch trees growing in a monoculture (variant I) were characterized by a considerable number of knots. The share of trees with this defect, which determined the result of wood classification, was almost 51%. The classification of the larch trees growing in the admixtures (variants II, III and IV) was particularly influenced by the stem curvature. The curvature determined the classification of almost 80% of these trees. On average, one-sided curvature and multilateral curvature contributed to 52.5 and 26.1% of wood defects, respectively.

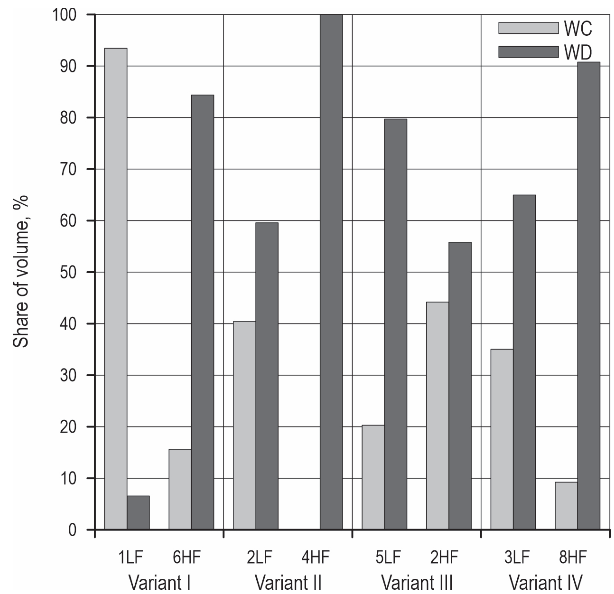

Fig. 3 Share of timber classes (4-meter-long butt sections) of trees growing in individual plots. Variant I refers to larch monoculture plots, variants II–IV refer to mixed stands (see Table 1 for details)

The greatest impact of knots on the wood quality classification was noted in trees growing in plot 1LF (less fertilized monoculture; about 93% of trees) (Fig. 5). On the contrary, the contribution of stem curvature to wood defects of 1LF trees was negligible. The greatest influence of one-sided curvature was observed in

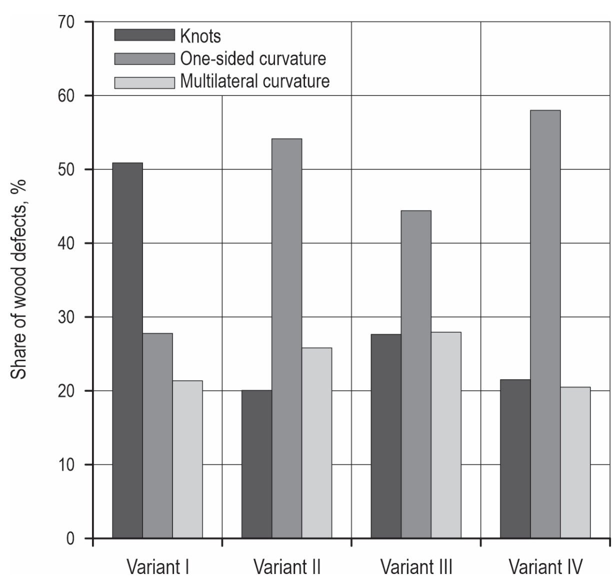

Fig. 4 Percentage share of wood defects disqualifying wood from being classified into higher quality-dimensional classes. Variant I refers to larch monoculture plots, variants II–IV refer to mixed stands (see Table 1 for details)

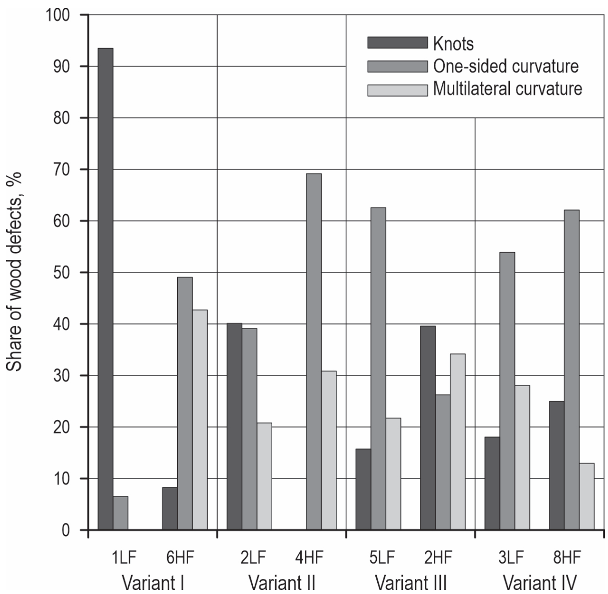

Fig. 5 Percentage share of wood defects disqualifying wood from being classified as higher quality-dimensional classes. Variant I refers to larch monoculture plots, variants II–IV refer to mixed stands (see Table 1 for details)

the 4HF plot (highly fertilized mixed stand with birch; 69.2% of trees in the plot), followed by plot 5LF (less fertilized mixed stand with locust and beech; 62.6%) and plot 8HF (highly fertilized mixed stand with alder and oak; 62.1%).

4. Discussion

Larch growing in fertile habitats and monocultures rapidly produces large volume increments (Olaczek 1986). Larch is regarded as a species resistant to atmospheric pollution and soil contamination and is therefore recommended for planting on mine dumps and heaps (Hendrychowá 2008, Krzaklewski 2017).

The average height of 40-year-old European larch has been estimated as 20.8 m (1st class of growth classification) under the optimal growth conditions, reaching only 17.7 m (2nd class of growth classification) under slightly worse conditions (Szymkiewicz 2001). Pazdrowski et al. (2007) found that larches growing in managed stands, on fresh mixed forest habitat, in age class II (up to 40 years old), reach an average height of 23.77 m and an average DBH of 24.18 cm. The above-presented growth parameters (Tables 2 and 4) indicate that the larch trees investigated in this study are in the lower class of growth classification. Only larches growing in the less-fertilized monoculture treatment reached heights similar to those of 1st growth class. Similarly, 25-year-old larch stands reached the 1st class of growth classification under the conditions of the recultivated external dump of the Sulphur Mine »Piaseczno« (Węgorek 2003). On the other hand, 30-year-old larches in the recultivated pit of the Szczakowa Sand Mine reached an average tree height between 16.2 and 9.9 m indicating growth classes I and III, respectively (Krzaklewski et al. 2011).

The highest volume of trunks per hectare was noted in the larch monoculture, and slightly lower volumes were found in stands admixed with beech and locust (variant III), as well as oak and alder (variant IV). A similar relationship was reported by Andrzejczyk et al. (2011), who concluded that larch volume depends on the share of beech trees in the stand. Increased share of beech in the stand reduced the volume of larch, although beech was present in the second storey of the stand. However, the study emphasized a positive impact of the lower forest storey on the quality of larch stands due to the stimulation of trees towards branch clearing. This is confirmed in our study, where, in the stands with an admixture of other species, the impact of knots on wood quality was low.

The most significant wood defects that disqualified wood from higher quality-dimensional classes were curvature (both single and multi-sided), and to a lesser extent, knots. It should be noted that in the monoculture (100% larch), wood quality was mainly influenced by knots, whereas in mixed stands, curvature was the main factor. Strong winds often cause young larch trees to lean out and trees to form trunks with a one-sided curvature as they try to regain the vertical position of the trunk (Bergstedt and Lyck 2007). This defect is accompanied by the formation of reaction wood, which can cause serious problems during the processing and drying. Trees with one-sided curvature should be separated from poor-quality trunks with multilateral curvature, which is largely a genetic trait and can only be limited by proper selection of species, origin and propagating material. The presence of trunk curvature can also be caused by larch canker (*Lachnellula willkommii*). This fungal pathogen can be largely avoided by selecting a resistant species or origin and planting larch in appropriate places. Szeligowski et al. (2010), investigating an occurrence of curvatures in European larch of various origins, found that the average number of curvatures per tree ranges from 1.38 to 2.42 occurrences (depending on the origin). They also observed that curvature decreased with tree age. This happens relatively slowly and over a longer period of time, which means that the technical quality of trees, determined on the basis of stem straightness, may change with age, and quality assessments carried out in younger development stages of the stand will usually be worse than when the stand is older.

Research on pine introduced into reclaimed areas also showed similar tendencies, which indicates that on poorer (sandy) or less fertilized deposits, coniferous trees grow better (Torbert et al. 1990, Pietrzykowski and Socha 2011, Pietrzykowski et al. 2015, Pająk et al. 2016). Some authors even indicate that pine introduced in post-mining areas grows better than in forest areas (Rodrigue et al. 2002, Kuznetsova et al. 2010). The effect of fertilization on the growth and development of Japanese larch (*Larix leptolepis* Sieb and Zucc.) 9 years after its introduction to plantations was studied by Kochenderfer et al. (1995). They showed that on non-fertilized soils, larch grew better and had larger sizes (height and DBH) as well as a greater share of trees in higher classes of vitality. They also found that nitrogen fertilization appears to be counterproductive and was not recommended. The more intensive fertilization (HF) carried out on the research plot in the initial stage of reclamation brought the expected results in terms of better growth of the introduced tree species, as reported by Krzaklewski et al. (1983, 1984). However, no such results have been observed n the long term. This may be due to the fact that the fertilization period is too short, especially since, according to Fiedler et al. (1974), larch grows well in soils that are rich in potassium, whereas the soils on the research plot showed a very low content of phosphorus from the very beginning (Krzaklewski et al. 1981). In contrast, Pajak et al. (2019, 2021), investigating the growth and quality of poplar wood introduced to the external dump in Bełchatów, showed that the quality of the substrate from which the top layer of the initial soils on the dump was shaped had a great influence on the studied parameters.

5. Conclusions

Higher growth parameters (mean height, mean DBH) were found in larch trees growing in monoculture than admixed with other tree species. Fertilization, applied in the initial afforestation period, had only a limited effect on the growth of larch trees

Growth conditions of external dump led to a low wood quality of larch trees, with the WD quality-dimensional class dominating. However, larches growing in the monoculture had a better wood quality (prevailing share of the WC class) as compared to larches growing mixed with other tree species.

Stem curvature (both single- and multi-sided) was identified as the main defect reducing wood quality. Knots have decisive importance only in larch trees growing in monocultures, but not in larch trees growing in mixed stands.

Our data show that the introduction of admixtures influences the timber quality of European larch planted under the extreme conditions of external dumps.

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