

Tree Crown Defoliation Degree as a Predictor of Silver Fir (*Abies alba* Mill) and Norway Spruce (*Picea abies* (L.) Karst.) Timber Value

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Abstract

Norway spruce (*Picea abies* (L.) Karst.) and silver fir (*Abies alba* Mill.) are both economically and ecologically important coniferous tree species in Europe. Due to climate change, both of them are affected by dieback. This paper examines the quantity, quality, and value of roundwood produced from healthy, severely defoliated (61–99%) and dead Norway spruce and silver fir trees. The study was conducted in four subcompartments located in the Forest Administration Delnice, Management Unit »Milanov vrh«. In total, 81 trees of silver fir (208.77 m³ of gross volume) and 83 trees of Norway spruce (208.43 m³ of gross volume) were measured. Study results showed that the measured gross volume of silver fir was by 8.29% higher than predicted by the harvesting plan, while the measured gross volume of Norway spruce was slightly higher by 0.90%. The determined assortment structure showed a negative correlation between tree crown defoliation degree and the share of highly valuable assortments for both researched species. Healthy trees of silver fir had the highest share of veneer logs, while dead silver fir trees had the highest share of pulpwood. Silver fir dead trees also had the highest share of waste (22.19%), while healthy and severely defoliated trees had 18.69% and 18.47%, respectively. In the case of Norway spruce, healthy trees had the highest share of veneer logs, while dead trees had the highest share of pulp wood. At the same time, the share of waste remains almost the same regardless of the tree crown defoliation degree (from 17.97% for dead trees to 18.17% for healthy trees). Results of the determined assortment structure reflected on the average tree value, which was also negatively impacted by the tree crown defoliation degree. In the case of silver fir, the value of dead trees along DBH classes was 25.6% to 41.6% lower than for healthy trees, while in the case of Norway spruce, the value of dead trees was 22.4% to 36.3% lower than that of healthy trees. The initial hypothesis that average tree value decreases in the order: healthy trees > severely defoliated trees > dead trees was confirmed. To improve harvesting plans, the inclusion of a tree crown defoliation degree as an additional predictor of assortment structure is strongly supported by the results of this study.

Keywords: tree decline, assortment structure, average tree value, wood defects

1. Introduction

Forests have always played an important role in providing many essential services such as biodiversity conservation and climate regulation (UNECE 2024), as well as the development of the economy and society, creating jobs and providing food, medicines, materials, clean water, and more (European Commis-

sion 2021). The trends in consumer preferences, as well as the price of the wood products and substitute products, population, and income levels, dictate demand for the forest products (Whiteman et al. 1999). For example, up to the 19th century, wood was mostly used as fuel, raw material for constructing, agriculture, crafts and shipbuilding (Gustavsson et al. 2006). Nowadays, the importance of forests is recognised through

many European policies (Patacca et al. 2023) with the main goal to preserve healthy forest ecosystems and promote sustainable forest management. The necessity of preserving forest ecosystems lies in the significant negative impact of climate change and rising tree canopy mortality rate (Senf et al. 2021, Bledý et al. 2024), which potentially leads to increased volume of low-quality timber.

Norway spruce (*Picea abies* (L.) Karst.) and silver fir (*Abies alba* Mill.) are both recognised as economically and ecologically most valuable coniferous tree species in Europe (Spiecker 2000, Dobrowolska et al. 2017). In Croatian forests, both species represent 78.9% of coniferous state-owned growing stock, in which 62.0% are silver fir trees. Both tree species are significantly affected by climate change, resulting in increased mortality rates. In 2024, in 42.06% of silver fir trees, crown defoliation of more than 25% was observed, which is a decrease of 22.15% compared to 2016 (Potočić et al. 2025). In contrast to silver fir, in 59.3% of Norway spruce trees in Croatian forests, crown defoliation of more than 25% was observed, while in the region of Gorski Kotar, 96.2% trees showed crown defoliation of more than 25% (Matić 2011).

Forestry profitability is influenced by timber price, which strongly depends on timber quality and species (Knoke et al. 2005) that can be defined from different points of view. In technical terms, timber quality depends on the intrinsic characteristics, key attributes, and factors influencing its suitability for specific use (Mitchell 1961, Jozsa and Middleton 1994, Nocetti et al. 2024). An expanded definition of wood quality that includes all participants in the wood supply chain is provided by Zhang (1997), who defines wood quality as the wood characteristics that influence the value recovery chain and the serviceability of end products. Following that, having an accurate estimate of timber quality distribution provides strong benefits on many levels in the wood supply chain. For example, forest owners and forest managers can adopt silvicultural measures to increase wood quality (Nocetti et al. 2024), e.g., thinning is one of the main silvicultural measures used to increase timber quality (Shifley 2002, Goncalves 2021, Speicker 2021). Besides the silvicultural practice, site factors as well as genetics can also play a significant role in timber quality (Macdonald and Hubert 2002). Further, during the stand rotation, numerous natural disturbances can occur that can negatively influence conditions in which the stands are developing and possibly influence timber quality. In the past decade in Croatian forests, three significant events occurred, which resulted in an increased

amount of sanitary felling (Đuka et al. 2025). The first and second events were in the Gorski Kotar region (ice storm in 2014 and bark beetle outbreak in 2017), and the last one was a windstorm in 2023 in the Slavonia region (Đuka et al. 2025).

In general, timber quality can be determined by measuring visual tree/roundwood features (e.g. dimensions and present wood defects) or by testing timber as material to determine its suitability for a specific purpose (e.g. tension strength, tension modulus of elasticity, etc.). Visual assessment of the timber quality can be done on standing trees, when grading produced roundwood, or after sawmill processing, with the latter being the most accurate (Karaszewski et al. 2013) due to the impossibility of assessing all wood defects in standing trees (Marenče et al. 2020). In Croatian forestry, assessment of timber quality is performed on the felling site or on the landing. It is based on measuring roundwood dimensions (diameter and length), determining and measuring present wood defects, and classifying roundwood into quality classes following the standard used.

The tree crown defoliation degree is an often used indicator of tree health and vigor (Ferretti et al. 2021), and it is also used as an indicator of air contamination (Augustaitis et al. 2010). Overall, many studies were focused on the correlation between tree crown defoliation degree and different types of stressors (Popa et al. 2017), to improve mortality models (Paixo et al. 2019), and to improve growth rate models (Dobbertin and Brank 2001).

In Croatian forestry, tree crown defoliation is used as a criteria when marking trees for felling, resulting with the number of live and dead marked trees at subcompartment level. This distribution is further used in creating harvesting plans, e.g., calculations of gross and net harvesting volume, quality distribution, and expected value of marked trees. Since the recent studies (Ursić et al. 2025, Ursić and Vusić 2025) showed discrepancies between expected and actual average tree value as well as differences along tree crown defoliation degree classes, this research aimed to determine:

- ⇒ quantity and quality of produced silver fir and Norway spruce assortments from dieback-affected trees
- ⇒ correlation between tree crown defoliation degree and wood defect presence
- ⇒ level of value reduction of dieback-affected trees.

The initial hypothesis of this research was that average tree value reduction is the highest in the case of dead trees followed by severe defoliated trees.

Table 1 Data on research locations and stand characteristics

Subcompartment		12b	14a	53a	55a
Coordinates		φ 45°36'56" N λ 14°33'01" E	φ 45°36'50" N λ 14°33'40" E	φ 45°38'57" N λ 14°34'27" E	φ 45°39'11" N λ 14°35'19" E
Area, ha		49.00	24.64	46.26	41.03
Phytocenosis		Omphalodo-Fagetum / Tregubov 1957 corr. Puncer 1980 / Marinček et al. 1993		Aremonio-Piceetum Horvat 1938	
Inclination, °		15–35	5–20	0–20	0–20
Stocking		1.04	0.99	0.71	0.92
Basal area, m ² /ha	European beech (<i>Fagus sylvatica</i> L.)	12.51	10.63	3.42	6.08
	Silver fir (<i>Abies alba</i> Mill)	13.67	16.87	15.87	20.02
	Norway spruce (<i>Picea abies</i> (L.) Karst.)	4.44	3.83	6.86	8.02
	Scots pine (<i>Pinus sylvestris</i> L.)	–	–	0.05	–
	OHB	1.06	0.58	0.52	0.74
Growing stock, m ³ /ha		403.0	365.0	321.0	482.0
Species composition, %	European beech (<i>Fagus sylvatica</i> L.)	39.4	30.7	8.1	12.6
	Silver fir (<i>Abies alba</i> Mill)	43.6	55.3	59.4	61.7
	Norway spruce (<i>Picea abies</i> (L.) Karst.)	13.3	12.4	30.9	24.0
	Scots pine (<i>Pinus sylvestris</i> L.)	–	–	0.3	–
	OHB	3.7	1.6	1.3	1.7

OHB – other hard broadleaves

2. Materials and Methods

2.1 Sample Preparation

The study was conducted in four subcompartments located in Forest Administration Delnice, Management Unit »Milanov vrh« (Table 1), where a combination of selective and salvage felling of silver fir and Norway spruce was performed. Tree marking was performed by Croatian experts from the company »Croatian Forests« Ltd., Zagreb, after which sample trees were randomly chosen. Sample trees were chosen based on their diameter at breast height (DBH) and tree crown defoliation degree (TCDD). Two perpendicular diameters at breast height (1.3 m above ground) were measured from the upper side of the slope. The tree crown defoliation degree was determined via visual estimation of crown area without needles. Following the ICP guidelines for visual assesment of the crown condition and damaging agents (Eichhorn et al. 2020), first, the healthy and

undefoliated trees (of both investigated tree species) were found, and then they were used as reference trees after which defoliation degree of defoliated tree was determined. Based on the TCDD, trees were classified in the following classes: healthy tree (H) if crown defoliation was less than 25%; severely defoliated tree (S) if the crown defoliation was 61–99%, and dead tree (D) if the crown was 100% defoliated (Fig. 1).

2.2 Tree Measurements

After sample trees were chosen, they were cut and processed into logs following the HRN standard (HRN D.B4.021, 1979; HRN D.B4.029, 1979; HRN D.B5.020, 1979), which classifies logs into grades based on their potential end use. Following the HRN standard, it was possible to produce veneer logs (VL), saw logs of the first quality class (SLI), saw logs of the second quality class (SLII), saw logs of the third quality class (SLIII), and pulp wood (PW). Additionally, quality classes were assigned according to the HRN EN

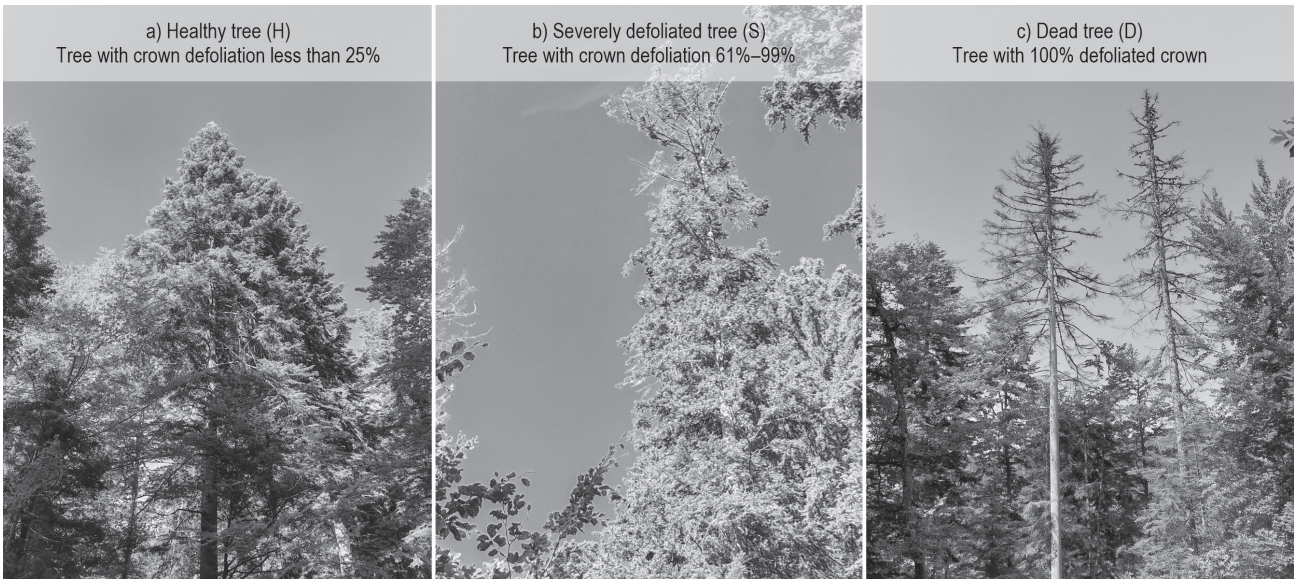


Fig. 1 Tree crown defoliation degree classes

1927-1:2008 standard, where grades are based only on the wood quality without indication of the wood end use. To assign the assortment class, the entrance criteria were dimensions of the produced log and present wood defects. Both standards have specific requirements for volume determination as stated in Table 2. On the tree level, measurements were performed in order to record actual log dimensions. The actual log length was measured with an accuracy of 0.01 m, and

two mid-length over-bark diameters were measured with an accuracy of 0.1 cm. Additionally, in the case of a butt log, the length of the notch cut was also measured with an accuracy of 0.01 m, as well as the unprocessed crown length.

The presence of wood defects was visually determined on the log cross-section and bark. If wood defects were present, additional measurements were performed to assess the significance of present wood

Table 2 Prescribed volume determination rules used by standards

Standard	JUS D.B0.022	HRN EN 1309-2
Length	⇒ The shortest length is measured with an accuracy of at least one centimetre ⇒ Timber with a notch cut or butt trimming should be measured from the end of the notch cut or butt trimming surface ⇒ Length is rounded to the nearest 1/4 m ⇒ The length allowance for the saw logs is minimum 5 cm and maximum 20 cm	⇒ The shortest length is measured with an accuracy of at least one centimetre ⇒ Timber with a notch cut or butt trimming should be measured from the middle of the notch cut or butt trimming surface ⇒ The length is expressed in metres rounded down to one decimal place ⇒ The length allowance is not given
Diameter	⇒ Measured two mid-length under bark diameters to an accuracy of at least one centimetre ⇒ In case of an over-bark measure, conversion to an under-bark diameter is necessary ⇒ The arithmetic mean of two measurements is rounded down to the nearest centimetre	⇒ Measured two mid-length under bark diameters to an accuracy of at least one centimetre ⇒ In case of an over-bark measure, conversion to an under-bark diameter is necessary ⇒ The arithmetic mean of two measurements is rounded down to the nearest centimetre
Volume calculation	$V = \frac{d^2 * 3.14}{40000} * l$	$V = \frac{d^2 * 3.1416}{40000} * l$

V – log volume
l – log length
d – log diameter

defects (e.g., knot size and frequency), and their influence on assortment quality. The presence of wood defects that did not allow the log classification into the highest quality class, if the dimensions criteria were met, was recorded. All data were recorded using UMTPlus Max 20.1.12 software, in which the interface was modified to allow recording data on the log dimensions, present wood defects, and quality classes on the tree level (Ursić and Vusić 2025).

2.3 Data Processing

After field measurements were done, the collected data was transformed from the UMTPlus software to the MS Excel 2412 data sheet. The database created in MS Excel was checked to determine the correctness of the data. For both investigated species, distributions of sampled trees regarding five-centimetre-wide DBH classes and TCDD classes were made. For each measured tree part with over-bark top diameter greater than 7 cm, gross volume was calculated based on the measured length and over-bark diameter using Huber’s formula. The tree gross volume was calculated by adding up the single tree part gross volumes. Log net volume was calculated based on the rounded dimensions according to the prescribed rules by the standard used, after which the tree net volume was calculated by adding single log net volume on the tree level. Based on the price list (fco. forests road) provided by »Croatian Forests« Ltd. (2025), the value of a single log and a single tree was calculated, after which the average tree value was calculated by dividing the total tree value by the net tree volume determined following HRN standard. Expected gross harvesting volume was calculated using single-entry volume tables prescribed by »Croatian Forests« Ltd.

The influence of wood defect presence on the timber grading was determined using MS Excel software. Log dimensions and minimum dimensions prescribed by the HRN standard for a particular quality

class were used to determine how many logs could potentially be classified into a particular quality class, but they were not, because of present wood defects. Further, the number of present wood defects across the quality classes and TCDD classes was expressed as a percentage of the total number of wood defects in each quality class and in each TCDD class. Additionally, the presence of wood defects was presented regarding the ordinal number of logs in the tree and by the average height of wood defects on the tree. The average height of wood defects was calculated based on the logs length, e.g., for the second log in the tree, the length of the first log and half the length of the second log were summed up to express the average height of those wood defect.

To perform statistical analyses, TIBCO Statistica 14.0.0.15 software was employed. The multiple linear regression analysis was used to determine the influence of tree height and tree diameter on the actual gross and net tree volume across TCDD. The influence of TCDD classes on the average tree value was determined by calculating the percentage deviation ($\Delta\text{EUR}/\text{m}^3$, %) between the average healthy tree value and the average tree value of severely defoliated and dead trees along DBH classes. Additionally, a *t*-test was used to determine whether discrepancies between expected and determined gross volume, and between determined net HRN and net HRN EN volume are statistically significant. Analysis of variance was used to determine the influence of DBH and TCDD class on net HRN volume and average tree value (EUR/m^3). If the analysis of variance showed statistically significant differences, the Unequal *N* *HSD* post-hoc test was used to determine significant difference. Descriptive statistics were used to present average, standard deviation, minimum, and maximum values of roundwood length, diameter, gross volume, and net HRN volume across tree species, quality classes, and TCDD classes. For all statistical tests, statistical significance was accepted at $\alpha < 0.05$.

Table 3 Number of sampled trees in terms of tree species, DBH, and TCDD classes

Tree species	Silver fir			Norway spruce		
DBH, cm	H	S	D	H	S	D
37.5	5	3	5	6	5	3
42.5	6	6	7	6	7	6
47.5	7	6	6	4	6	4
52.5	7	6	7	5	8	5
57.5	2	3	5	5	7	6
Total	27	24	30	26	33	24

DBH – diameter class; H – tree with crown defoliation less than 25%; S – tree with crown defoliation 61%–99%; D – tree with 100% defoliated crown

3. Results

In total, 81 trees of silver fir and 83 trees of Norway spruce were sampled. Distribution of sampled trees in terms of TCDD and DBH classes is shown in Table 3.

3.1 Gross and Net Volume

The parameters of multiple regression showed statistically significant influence of tree height and diameter at breast height on the measured gross volume for both researched species, regardless of tree crown defoliation degree (Table A1 and A4). The measured gross volume of silver fir amounted to 208.77 m³ and of Norway spruce to 208.43 m³. For silver fir, the measured gross volume was 8.29% higher compared to the expected gross volume calculated using prescribed single-entry volume tables. In the case of Norway spruce, prescribed single-entry volume tables also predicted lower gross volume, but only by 0.90%. Param-

eters of the *t*-test (Table 4) showed no statistically significant differences between measured and expected gross volume for silver fir ($p=0.1035$) and Norway spruce ($p=0.8695$).

According to the HRN standard, the total calculated net volume was 167.05 m³ and 170.76 m³ for silver fir and Norway spruce, respectively. According to the HRN EN standard, the calculated net volume was 1.95% higher for silver fir and 2.25% higher for Norway, without statistically significant differences for both investigated species (Table 5).

Except for the prescribed volume calculation rules, both HRN and HRN EN net volumes were significantly influenced by DBH and tree height along both researched species and TCDD classes (Table A2, A3, A5, and A6). Additionally, analysis of variance showed no statistically significant influence of TCDD class on the determined HRN net volume (Table 6).

Table 4 *t*-test parameters of determined and expected gross volume (m³)

Tree species	Mean D	Mean E	<i>t</i> -value	<i>df</i>	<i>p</i>	<i>N</i>	<i>SD</i> D	<i>SD</i> E	<i>F</i> -ratio variances	<i>p</i> variance
Silver fir	2.5774	2.3637	1.6376	160.0000	0.1035	81	0.9213	0.7285	1.5993	0.0372
Norway spruce	2.5112	2.4886	0.1646	164.0000	0.8695	83	0.9297	0.8403	1.2242	0.3615

D – determined gross volume; E – expected gross volume; *SD* – standard deviation

Table 5 *t*-test parameters of determined HRN and HRN EN net volume (m³)

Tree species	Mean HRN	Mean HRN EN	<i>t</i> -value	<i>df</i>	<i>p</i>	<i>N</i>	<i>SD</i> HRN	<i>SD</i> HRN EN	<i>F</i> -ratio variances	<i>p</i> variance
Silver fir	2.0623	2.1026	−0.3361	160.0000	0.7373	81	0.7559	0.7695	1.0362	0.8741
Norway spruce	2.0573	2.1035	−0.3823	164.0000	0.7027	83	0.7685	0.7897	1.0558	0.8063

HRN – net volume according to HRN standard; HRN EN – net volume according to HRN EN standard; *SD* – standard deviation

Table 6 Influence of TCDD and DBH classes on the net HRN volume (m³)

Tree species	Effect	Degr. of freedom	SS	MS	<i>F</i>	<i>p</i>
Silver fir	<i>Intercept</i>	1	313.9134	313.9134	2246.356	<0.000001
	TCDD	2	0.0634	0.0317	0.227	0.797726
	DBH	4	34.9820	8.7455	62.582	<0.000001
	TCDD*DBH	8	0.4461	0.0558	0.399	0.917219
	<i>Error</i>	66	9.2231	0.1397	–	–
Norway spruce	<i>Intercept</i>	1	309.2852	309.2852	2099.578	<0.000001
	TCDD	2	0.2083	0.1042	0.707	0.496690
	DBH	4	36.3802	9.0951	61.742	<0.000001
	TCDD*DBH	8	0.3494	0.0437	0.297	0.964785
	<i>Error</i>	68	10.0170	0.1473	–	–

TCDD – tree crown defoliation degree; DBH – diameter at breast height; SS – sum of squares; MS – mean square

3.2 Features of Produced Roundwood

Descriptive statistics of produced roundwood are shown in Appendix A Table A7 for silver fir and Table A8 for Norway spruce. In total, 326 logs of silver fir and 367 logs of Norway spruce were produced. Regarding the quality classes, 3 VL, 34 SLI, 80 SLII, 84 SLIII, and 125 PW were produced from silver fir trees, and 5 VL, 26 SLI, 84 SLII, 125 SLIII, and 127 PW were produced from Norway spruce trees.

The first criteria that must be met to classify a log into a particular quality class are dimensions. Furthermore, information about log under-bark diameter is important when the unit price is created based on the quality class and diameter class, which is the case in the Croatian forestry. The deviation in under-bark log diameter along TCDD classes and quality classes is shown in Fig. 2a for silver fir and in Fig. 2b for Norway spruce. It is obvious that the average log diameter depends on the TCDD class since healthy trees almost always had a smaller average diameter along quality classes, except in the case of silver fir, where SLI logs produced from healthy trees had slightly higher average under-bark diameter. This trend is probably caused by the presence of wood defects. Namely, the second criteria during roundwood grading were the allowed wood defects prescribed by the standard used. Based on the results, it seems that the lower part of dead trees had a higher share of unallowed wood defects in comparison to the H and S trees, because of which they were classified into lower quality classes regardless of

their dimensions. Following that, additional analysis was done to detect whether the share of wood defects depends on the TCDD class.

3.2.1 Influence of Wood Defects on Silver fir Roundwood Grading

In the total number of wood defects, rot accounted for the highest share (23.5%) followed by intergrown sound knots (23.1%), unsound knots (18.3%), covered knots (12.8%), sound dead knots (11.7%), insect holes bigger than 3.0 mm (6.0%), insect holes smaller than 3.0 mm (3.3%) and stain (1.4%). The number of logs that could be potentially classified into a particular quality class based on their dimensions, but were not, as well as the share of determined wood defects (by number of occurrences) that negatively affect log quality are shown in Table 7. In total, 136 silver fir potential veneer logs were mostly declassified because of: covered knots in the case of H trees; unsound knots in the case of S trees; and rot in the case of D trees. Potential silver fir veneer logs were mostly declassified into SLI and SLII classes in the case of H and S trees, while in the case of D trees they were mostly declassified into SLIII and PW classes. Silver fir potential SLI logs were mostly declassified because of intergrown sound knots in the case of H and S trees, while in the case of D trees the main reason was rot. Generally, intergrown sound knots were the most frequent limiting factor for logs produced from H trees to be classified into the highest quality class (based on their dimensions), while rot and insect holes were the most limiting factors in the case of D trees.

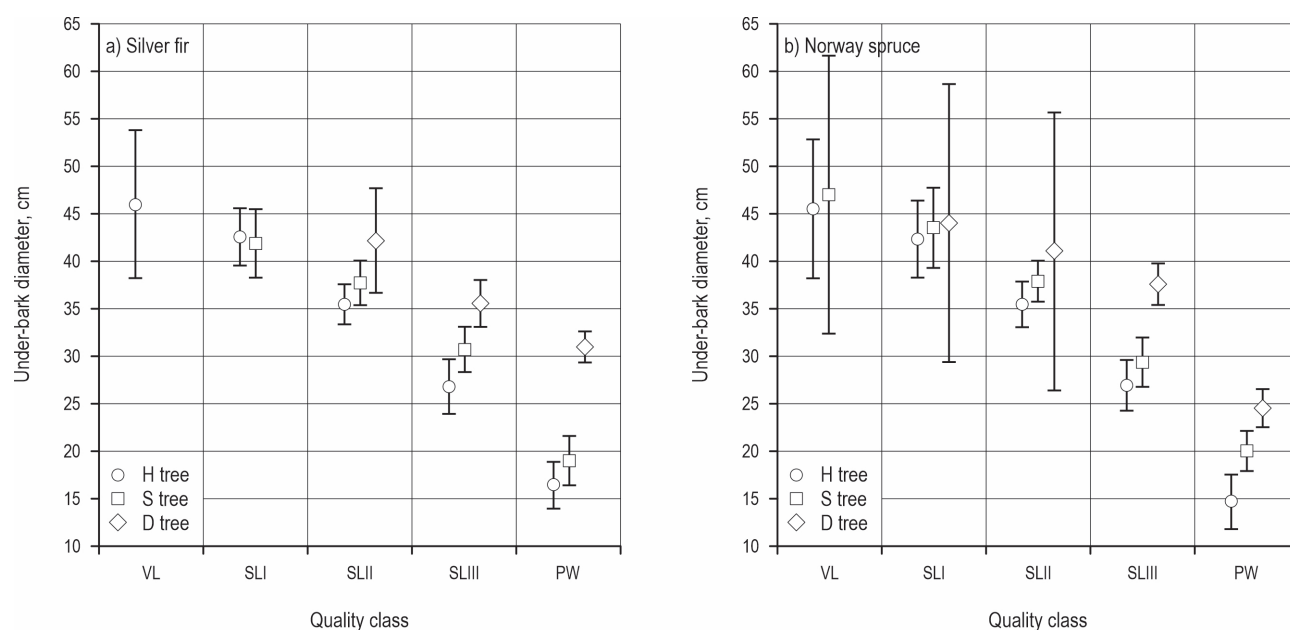


Fig. 2 Under-bark diameter along quality classes and tree crown defoliation classes (vertical bars denote 0.95 confidence intervals)

Table 7 Share (%) of present wood defects along quality classes and TCDD classes on measured silver fir logs

TCDD		QC	<i>N</i>	Covered knots	Intergrown sound knots	Dead sound knots	Unsound knots	Stain	Rot	Insect holes >3.00 mm	Insect holes <3.00 mm
Declassified VL	Healthy fir tree	I	20	50.00	36.36	4.55	9.09	—	—	—	—
		II	23	25.00	28.85	11.54	30.77	3.85	—	—	—
		PW	1	—	—	—	—	—	100.00	—	—
		Total	44	32.00	30.67	9.33	24.00	2.67	1.33	—	—
	Severely defoliated fir tree	I	12	50.00	14.29	14.29	21.43	—	—	—	—
		II	20	17.95	28.21	7.69	38.46	7.69	—	—	—
		III	11	4.55	22.73	31.82	36.36	—	4.55	—	—
		PW	1	—	—	—	—	—	100.00	—	—
		Total	44	19.74	23.68	15.79	34.21	3.95	2.63	—	—
	Dead fir tree	II	6	36.36	—	27.27	9.09	9.09	—	18.18	—
		III	17	12.50	12.50	10.00	20.00	—	15.00	17.50	12.50
		PW	25	—	2.63	2.63	2.63	—	60.53	23.68	7.89
		Total	48	10.11	6.74	8.99	11.24	1.12	32.58	20.22	8.99
Declassified SLI	Healthy fir tree	II	18	18.42	39.47	23.68	18.42	—	—	—	—
		III	15	4.76	61.9	4.76	23.81	—	4.76	—	—
		Total	33	13.56	47.46	16.95	20.34	—	1.69	—	—
	Severely defoliated fir tree	II	13	18.52	29.63	18.52	29.63	3.70	—	—	—
		III	16	3.45	51.72	24.14	20.69	—	—	—	—
		PW	3	—	33.33	—	33.33	—	33.33	—	—
		Total	32	10.17	40.68	20.34	25.42	1.69	1.69	—	—
	Dead fir tree	III	12	7.41	18.52	18.52	11.11	—	14.81	14.81	14.81
		PW	24	3.03	3.03	—	9.09	—	54.55	27.27	3.03
		Total	36	5.00	10.0	8.33	10.0	—	36.67	21.67	8.33
Declassified SLII	Healthy fir tree	III	7	—	55.56	22.22	22.22	—	—	—	—
		PW	3	—	100.00	—	—	—	—	—	—
		Total	10	—	60.00	20.00	20.00	—	—	—	—
	Severely defoliated fir tree	III	5	12.50	25.00	25.00	25.00	—	12.5	—	—
		PW	4	—	50.00	—	—	—	50.00	—	—
		Total	9	10.00	30.00	20.00	20.00	—	20.00	—	—
	Dead fir tree	III	1	—	—	—	—	—	50.00	—	50.00
		PW	6	—	14.29	14.29	14.29	—	42.86	—	14.29
		Total	7	—	11.11	11.11	11.11	—	44.44	—	22.22
Declassified SLIII	Healthy fir tree	PW	3	—	100.00	—	—	—	—	—	—
	Severely defoliated fir tree	PW	3	—	100.00	—	—	—	—	—	—
	Dead fir tree	PW	3	—	100.00	—	—	—	—	—	—

Except for the share of each wood defect, additional analysis was done to determine wood defect presence according to the ordinal number of the log in the tree (Fig. 3) and according to the height of the wood

defect (Fig. 4). The appearance of knots by their type follows a logical trend where the lowest part of the tree mostly had covered knots, and by rising height knots appeared in the following order: unsound knots,

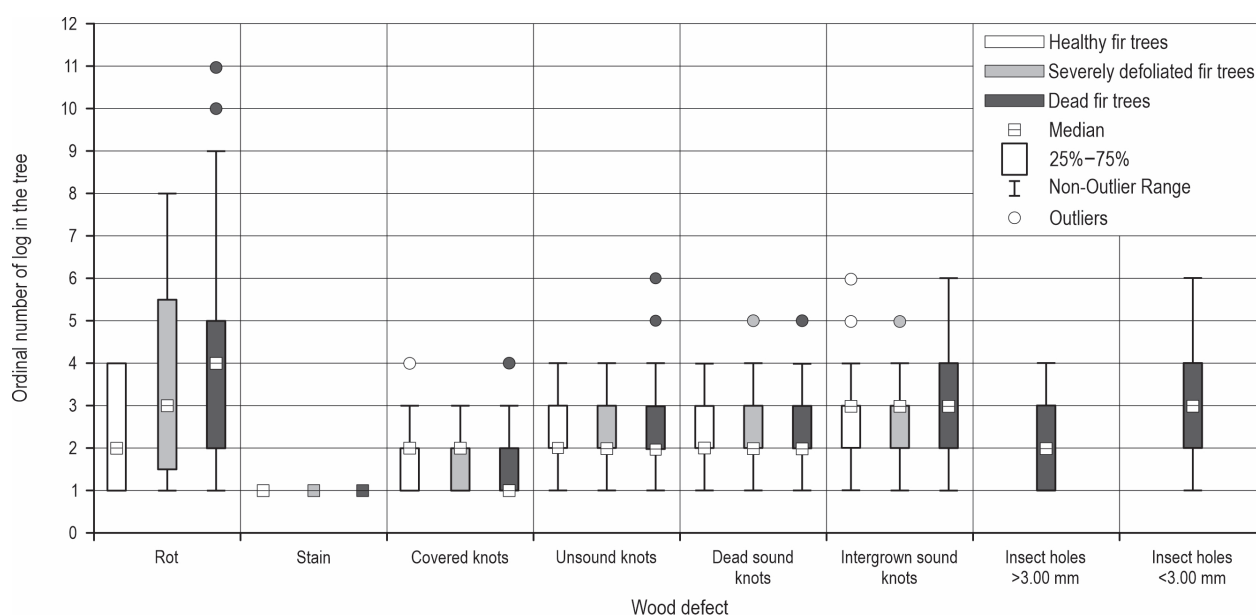


Fig. 3 The average ordinal number of log in the tree where wood defect was present

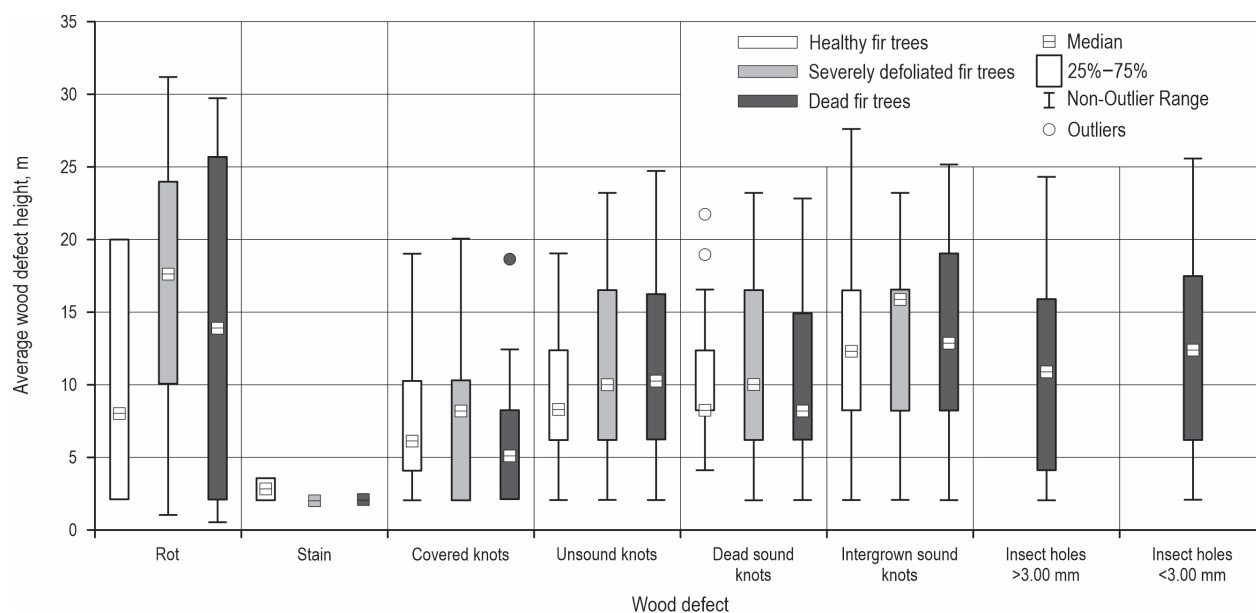


Fig. 4 The average height (m) of wood defects

sound dead knots and intergrown sound knots. Further, stain as an initial stage of rot was present only on the lowest part of the tree along all TCDD classes, while rot was present in the higher parts of D trees in comparison to H and S trees.

3.2.2 Influence of Wood Defects on Norway Spruce Roundwood Grading

In the total number of wood defects, intergrown sound knots accounted for the highest share (33.1%)

followed by covered knots (15.7%), sound dead knots (13.0%), rot (12.8%), insect holes smaller than 3.0 mm (9.1%), unsound knots (6.6%), stain (5.5%) and insect holes bigger than 3.0 mm (4.2%). The number of logs that could be potentially classified into a particular quality class based on their dimensions, but were not, as well as the share of determined wood defects (by number of occurrences) that negatively affect log quality are shown in Table 8. In total, 136 Norway spruce potential veneer logs were declassified because of:

Table 8 Share (%) of present wood defects along quality classes and TCDD classes on measured Norway spruce logs

TCDD		QC	N	Covered knots	Intergrown sound knots	Dead sound knots	Unsound knots	Stain	Rot	Insect holes >3.00 mm	Insect holes <3.00 mm
Declassified VL	Healthy spruce tree	I	12	43.75	43.75	12.50	–	–	–	–	–
		II	20	17.5	45.00	15.00	17.50	2.50	–	–	2.50
		III	2	–	50.00	–	25.00	–	25.00	–	–
		Total	34	23.33	45.00	13.33	13.33	1.67	1.67	–	1.67
	Severely defoliated spruce tree	I	11	50.00	18.75	25.00	6.25	–	–	–	–
		II	33	28.33	33.33	15.00	11.67	8.33	–	–	3.33
		III	10	16.67	20.83	16.67	20.83	–	12.50	–	12.50
		PW	7	12.5.0	–	–	–	–	87.50	–	–
		Total	61	27.78	25.93	15.74	12.04	4.63	9.26	–	4.63
	Dead spruce tree	I	1	100.00	–	–	–	–	–	–	–
		II	1	50.00	–	–	–	–	–	–	50.00
		III	30	5.36	7.14	5.36	3.57	19.64	26.79	14.29	17.86
		PW	9	–	7.69	–	–	–	46.15	23.08	23.08
		Total	41	6.94	6.94	4.17	2.78	15.28	29.17	15.28	19.44
Declassified SLI	Healthy spruce tree	II	16	29.03	38.71	22.58	6.45	3.23	–	–	–
		III	18	9.09	77.27	9.09	–	–	–	–	4.55
		PW	1	–	100.00	–	–	–	–	–	–
		Total	35	20.37	55.56	16.67	3.70	1.85	–	–	1.85
	Severely defoliated spruce tree	II	13	14.81	44.44	22.22	11.11	–	–	–	7.41
		III	26	8.89	53.33	22.22	2.22	–	6.67	–	6.67
		Total	39	11.11	50.00	22.22	5.56	–	4.17	–	6.94
	Dead spruce tree	III	14	–	5.56	–	–	27.78	27.78	22.22	16.67
		PW	12	4.55	18.18	9.09	–	4.55	36.36	13.64	13.64
		Total	26	2.50	12.50	5.00	–	15.00	32.50	17.50	15.00
Declassified SLII	Healthy spruce tree	III	9	–	75.00	25.00	–	–	–	–	–
		Total	9	–	75.00	25.00	–	–	–	–	–
	Severely defoliated spruce tree	III	13	–	76.92	15.38	–	–	–	–	7.69
		PW	4	–	–	–	–	–	–	–	100.00
		Total	17	–	71.43	14.29	–	–	–	–	14.29
	Dead spruce tree	III	1	–	–	–	–	–	50.00	–	50.00
		PW	9	16.67	–	–	–	16.67	33.33	–	33.33
		Total	10	12.50	–	–	–	12.50	37.5	–	37.50
Declassified SLIII	Severely defoliated spruce tree	PW	4	–	–	–	–	–	–	–	100.00
	Dead spruce tree	PW	9	16.67	–	–	–	16.67	33.33	–	33.33

intergrown sound knots in the case of H trees; covered knots in the case of S trees; and rot in the case of dead trees. Potential Norway spruce VL were mostly declassified into SLI and SLII classes in the case of H and S trees, while in the case of D trees, they were mostly

declassified into the SLIII class. Potential Norway spruce SLI logs were mostly declassified because of intergrown sound knots in the case of H and S trees, while in the case of dead trees, the main reason for declassification was rot. Generally, the same trend as

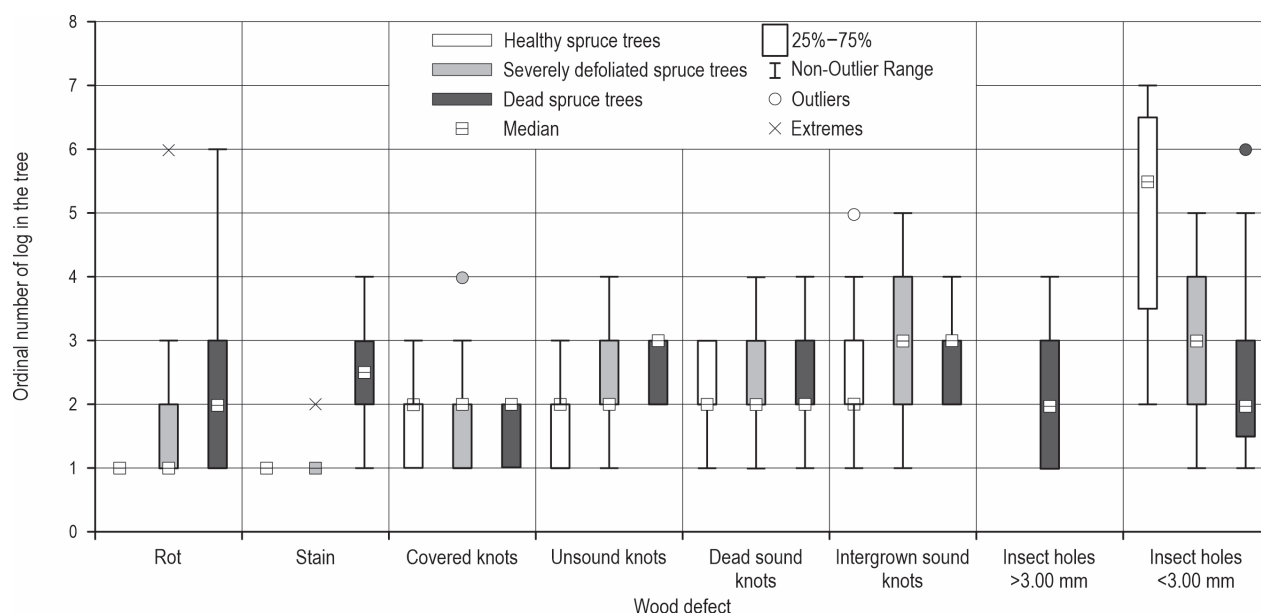


Fig. 5 The average ordinal number of log in the tree where wood defect was present

in the case of silver fir was found for Norway spruce; intergrown sound knots were the most frequent limiting factor for logs produced from H trees to be classified into the highest quality class (based on their dimensions), while rot and insect holes were the most limiting factors in the case of D trees.

The presence of wood defects according to the ordinal number of the log in the tree is shown in Fig. 5, and according to the height of wood defect in Fig. 6. The same trend of knots appearing as for silver fir is noticed

in the case of Norway spruce; knots appear by height in the following order: covered knots < unsound knots < sound dead knots < intergrown sound knots. Appearance of rot was also noticed in higher parts of D trees compared to H and S trees. Furthermore, in the case of the knots (for both investigated species), the average height of their appearance was quite similar regardless of TCDD class, indicating that growing conditions, management measures, and species characteristics may have had a stronger influence than TCDD class.

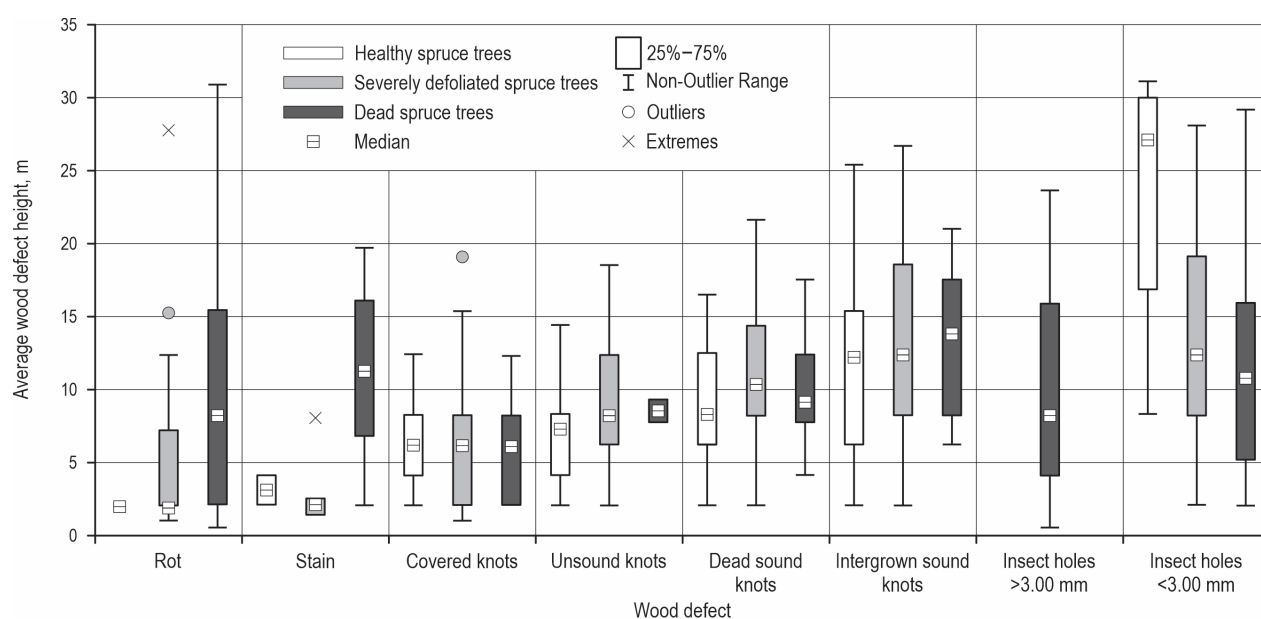


Fig. 6 The average height (m) of wood defects

3.3 Determined Assortment Structure

Determined assortment structure following HRN standard quality grades on the research sites along TCDD classes is shown in Fig. 7 for silver fir and in Fig. 8 for Norway spruce. Determined assortment structure according to the HRN EN standard is shown in Appendix A, Fig. A1 for silver fir and Fig. A2 for Norway spruce.

Determined assortment structure for silver fir showed the influence of TCDD class on the share of highly valuable assortments, e.g., VL were only pro-

duced from H trees, while VL and SLI logs were completely absent in the case of D silver fir trees. Absence of VL logs in DBH 57.5 cm of healthy trees could be explained by the presence of covered and dead knots, which were present mostly on the first and second log, from which it is supposed that VL can be produced. On the other side, the share of PW was the lowest in the case of H trees (3.82%), while it was significantly higher in the case of D trees (38.58%). The share of sawlogs was the highest in the case of S trees (74.78%), followed by H trees (72.56%) and D trees (30.11%). This trend could be explained by the absence of VL

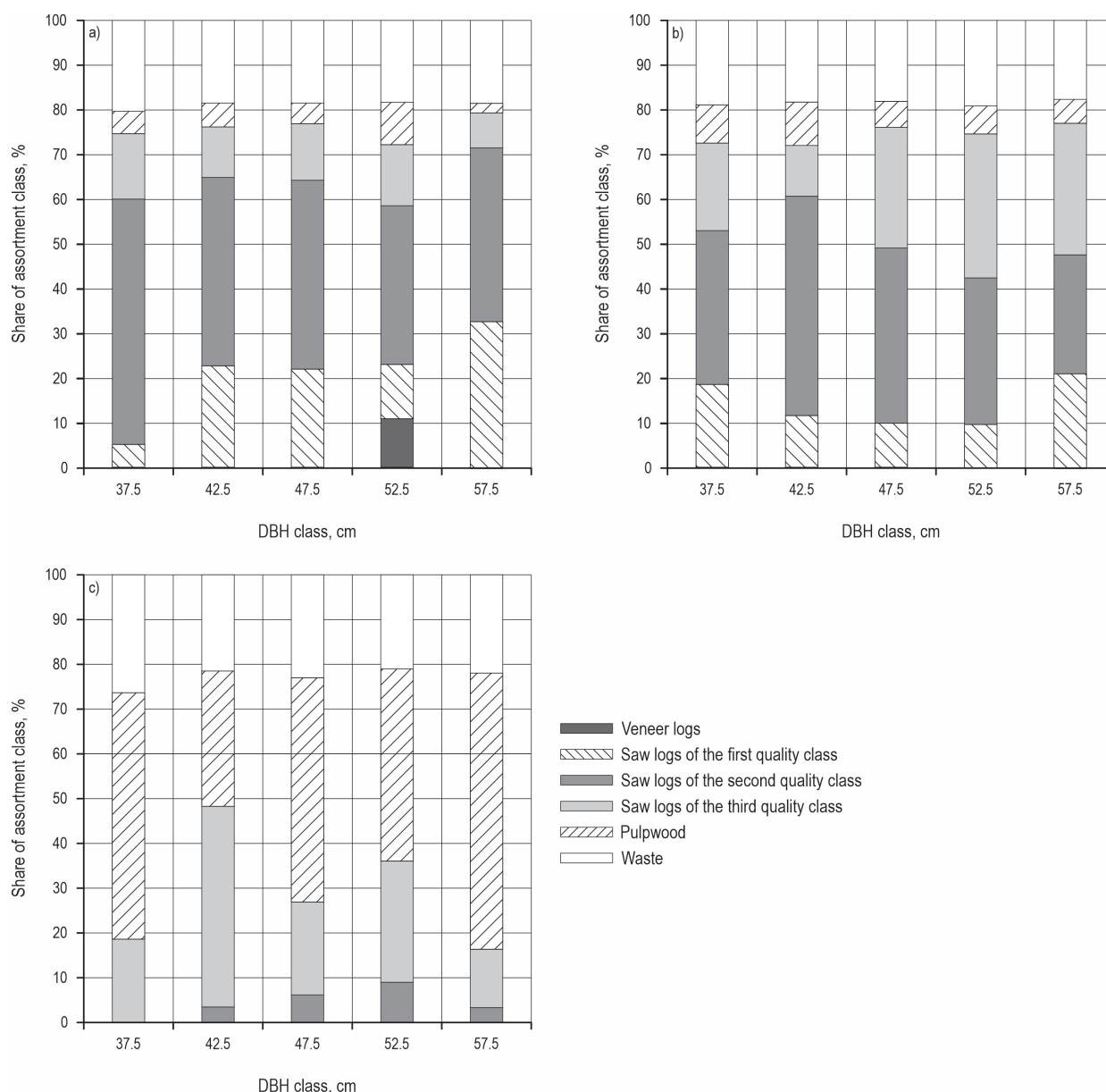


Fig. 7 Silver fir assortment structure according to HRN grading classes: a) for healthy fir trees, b) for severely defoliated fir trees, c) for dead fir trees

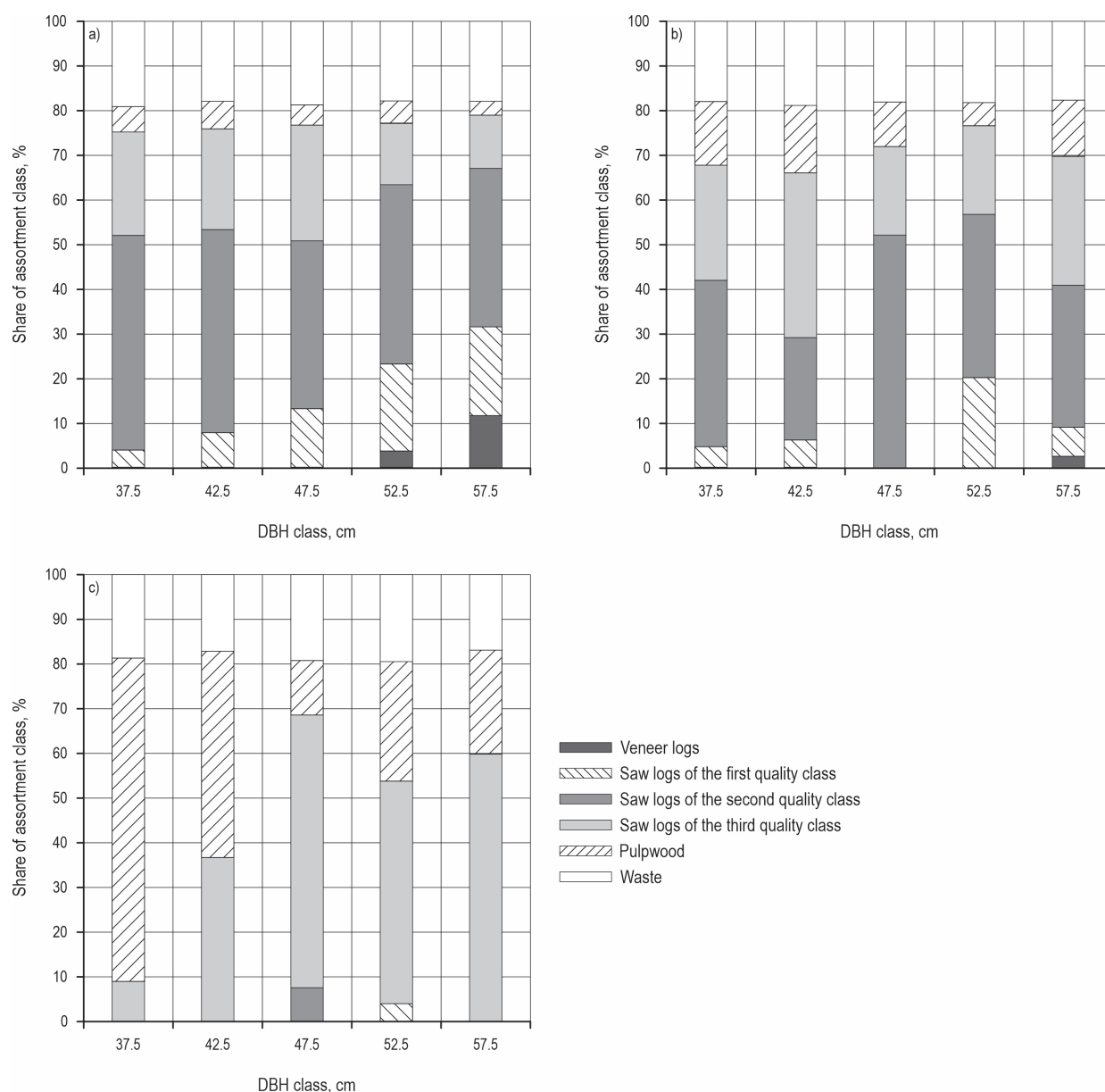


Fig. 8 Norway spruce assortment structure according to HRN grading classes: a) for healthy spruce trees, b) for severely defoliated spruce trees, c) for dead spruce trees

logs in the case of S trees, while a significantly lower share of sawlogs in the case of D trees is the result of a higher share of waste and PW. Namely, the highest share of waste was present in the case of D trees (22.19%), followed by H trees (18.69%) and S trees (18.47%).

In the case of Norway spruce, a determined assortment structure also showed the influence of TCDD class on the share of highly valuable assortments, e.g., the highest share of VL was produced from H trees, while VL logs were completely absent in the case of D Norway

spruce trees. The highest share of saw logs was produced from H trees (72.67%), followed by S trees (70.50%) and D trees (50.77%). The average share of waste was 18.07% with low deviation between TCDD classes (from 17.97% for D trees to 18.17% for H trees).

3.4 Average Tree Value

The deviation in average tree value of defoliated and dead trees in comparison to H trees is shown in Fig. 9a for silver fir and in Fig. 9b for Norway spruce as the final result of this study. The general trend

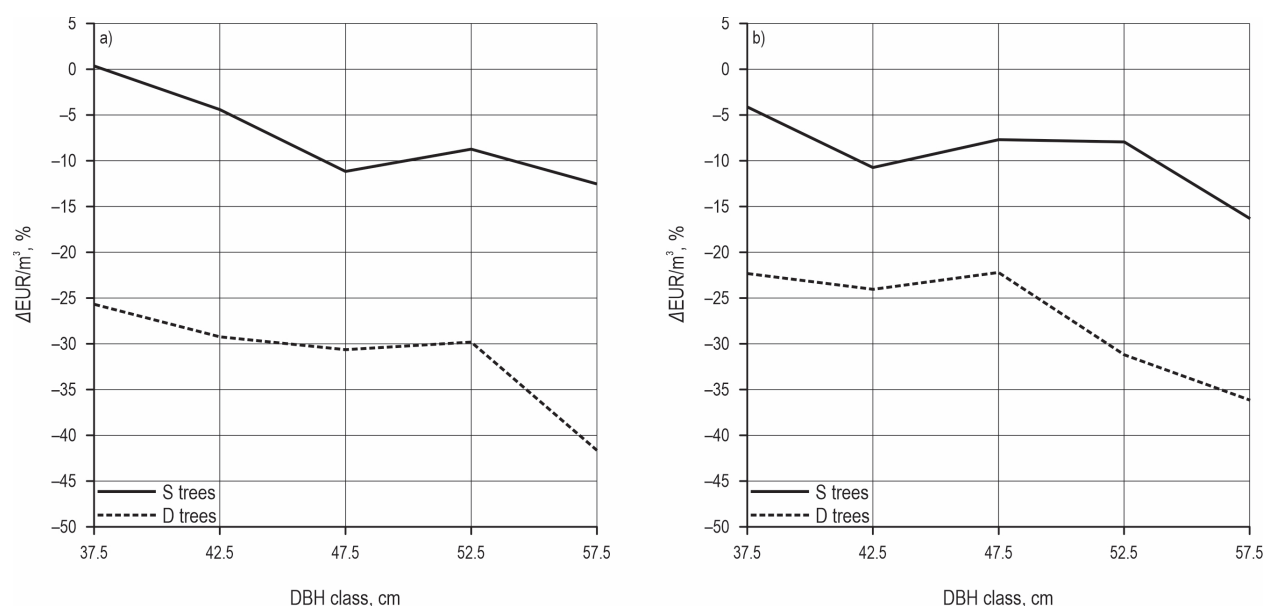


Fig. 9 Influence of TCDD class on the average tree value: a) for silver fir, b) for Norway spruce

shows a negative correlation between TCDD class and the average tree value. A slightly higher (0.25%) average tree value was determined in DBH class 37.5 for S silver fir trees, while in other TCDD and DBH classes, S and D trees always had a lower average tree value for both investigated species. Also, for silver fir, the largest decrease in the average tree value of 41.6% (DBH class 57.5) was detected for D trees. In the case of Norway spruce, the value of S trees decreased from 4.14% in DBH class 37.5 to 16.38% in DBH class 57.5, while the decrease of D trees in average tree value was significantly higher, from 22.39% in DBH class 37.5 to 36.3% in DBH class 57.5. In the case of D trees, silver fir trees showed a larger decrease in average tree value

along all DBH classes compared to Norway spruce trees, while silver fir S trees showed a lower decrease in average tree value in DBH classes 37.5, 42.5, and 57.5 than Norway spruce S trees.

As a final result of this study, the average tree value was expressed in EUR/m^3 and statistically tested to determine whether it depends on the DBH class and TCDD class, and whether their interaction has a statistically significant influence. Analysis of variance (Table 9) showed statistically significant influence of DBH and TCDD class on the average tree value, while the interaction of TCDD and DBH class was not statistically significant. Although the statistical test did not show a significant influence of DBH and TCDD

Table 9 Influence of TCDD degree on average tree value (EUR/m^3)

Tree species	Effect	Degr. of freedom	SS	MS	F	p
Silver fir	Intercept	1	248632.8	248632.8	6781.690	<0.000001
	TCDD	2	6454.9	3227.5	88.032	<0.000001
	DBH	4	1005.4	251.3	6.856	0.000112
	TCDD*DBH	8	443.2	55.4	1.511	0.170314
	Error	66	2419.7	36.7	—	—
Norway spruce	Intercept	1	255271.1	255271.1	4406.225	<0.000001
	TCDD	2	3816.3	1908.2	32.937	<0.000001
	DBH	4	2530.1	632.5	10.918	<0.000001
	TCDD*DBH	8	467.4	58.4	1.008	0.438081
	Error	68	3939.5	57.9	—	—

TCDD – tree crown defoliation degree; DBH – diameter at breast height; SS – sum of squares; MS – mean square

interaction on the average tree value, it is obvious that the average tree value is positively correlated with DBH class and negatively correlated with TCDD class. Furthermore, regression analysis (Fig. A3) showed a gentle introduction to linear regression in the case of D trees for both investigated tree species, which also indicates a lower quality of produced roundwood from D trees and quite similar quality regardless of DBH. In contrast to D trees, H and S trees showed steeper slope of linear regression and higher determination coefficient indicating a stronger dependence between DBH and quality of produced roundwood.

An additional post-hoc test showed that in the case of silver fir, D trees had the lowest average tree value (46.81 EUR/m³), followed by S trees (62.01 EUR/m³) and H trees (66.69 EUR/m³) with statistically significant differences between TCDD classes (Table A9). In the case of Norway spruce, D trees also had the lowest average tree value (47.75 EUR/m³), followed by S trees (60.32 EUR/m³) and H (65.26 EUR/m³), while only D trees were statistically significantly different from H and S trees (Table A9).

4. Discussion

Accelerated climate change poses a great challenge to the sustainability of forest ecosystems, sustainable forest management, and the production of high-quality timber assortments. Namely, recent studies determined a discrepancy between the established harvesting plans (on both national and stand level) and the actual harvested timber volume and value (Mederski et al. 2021, Ursić et. al. 2025, Ursić and Vusić 2025), which presents a large problem in the long-term and sustainable planning. This study was motivated by reduced volume utilisation and tree value, as a highly valuable renewable resource, due to the present climate change, and consequently increased sanitary felling in Croatian forests.

The deviation between the expected and actual timber volume processed could always be expected because of numerous reasons, e.g., trees and timber in general are a very heterogeneous material in which two identical trees or logs can rarely be found. Further, the number of input variables and calculation methods will strongly influence the deviation rate. For example, in the case of Turkey oak, the double-entry volume equation will estimate volume more accurately than the single-entry volume equation (Sönmez et al. 2022). According to the previous research, the deviation between the expected and actual gross volume is mostly within $\pm 2.5\%$ (Daniš and Neruda 2020), while the deviation of $\pm 10\%$ is considered very good (Brack

and Wood 1998). Results of this study showed the deviation between the determined and expected gross volume of 0.90% in the case of Norway spruce, which is quite low, while the deviation of 8.29% in the case of silver fir was confirmed as statistically significant. The prescribed volume determination rules also play an important role in volume determination since the determined HRN and HRN EN net volumes were statistically significantly different for both researched species. In Croatia, a gross volume calculation method is prescribed by the Regulation on tree marking, classification of forest products, consignment notes, and forest order (Ministry of Agriculture, Forestry and Fisheries 2019). Following this, the number of marked trees in each DBH class is multiplied by the single-entry table prescribed volume, which was obtained by measuring 1.0–3.0 m long tree parts. In this research, gross volume was determined by measuring produced log assortments that were commonly significantly longer than 3.0 m. In the case of silver fir, a higher expected gross volume could have been affected by an inappropriately chosen single-entry volume table.

Forest management requires tools for developing accurate harvesting plans. For example, an efficient and accurate timber measurement is highly important for timber trade transparency (Tomczak et. al. 2024), while an accurate estimated assortment structure can provide multiple benefits for all participants in the wood supply chain, even in harvesting efficiency calculation (Papandrea et al. 2025). Assortment structure, except for the timber dimensions and quality, also depends on the prescribed rules by the standard used. The numerous different standards have unique rules for the classification of produced logs into quality classes. Faced with those limitations, very few studies were conducted with the aim of researching the silver fir and Norway spruce assortment structure following HRN and HRN EN standards. The results of this study showed a negative correlation between TCDD class and highly valuable assortments, e.g., veneer logs, and a positive correlation between TCDD class and low-quality timber, e.g., pupwood. This trend strongly supports the idea of using the TCDD class in creating future assortment tables in order to have more accurate assortment tables and consequently to develop more accurate harvesting plans.

The presence of wood defects plays an important role in roundwood grading. Only 15.03% of silver fir logs and 22.34% of Norway spruce logs were classified into quality classes based solely on their dimensions. On research sites, the share of knots was significantly high, 65.9% for silver fir and 68.4% for Norway spruce.

The conducted studies also showed that knots are the most influential factors in roundwood grading in silver fir (Šušnjar et al. 2006) and Norway spruce trees (Berezjuk et al. 2025). Further, the height of knot appearance strongly influenced the declassification of the lower tree part from which highly valuable assortments could be produced. It is detected that wood defects related to the biological degradation are more common on D trees than on H and S trees. Namely, insect damage in the case of silver fir were present only on D trees, and the share of rot was always higher on the logs produced from D trees. A similar trend was observed in the case of Norway spruce, but with detected insect damage on H trees, which is most likely caused by a recent bark beetle outbreak in Croatia (Đuka et al. 2025). The negative influence of insect-infested trees is recognised through reduced tensile strength in comparison to uninfested Norway spruce trees (Löwe et al. 2022). In total, Norway spruce trees had a lower rot share than silver fir trees, indicating a higher durability of Norway spruce trees.

The final part of the study addressed the average tree value along DBH and TCDD classes. As presented, the average tree value was strongly influenced by TCDD class for both investigated tree species. A similar trend was reported by Zečić et al. (2009), where silver fir trees with defoliated crowns of 81–99% had 10–30% lower average value, while dead trees had 30–45% lower average value in comparison to healthy trees.

Further steps in research related to the assortment structure assessment should be directed towards the development of verified models since accurate assortment structure estimation models (which are still lacking) are a very valuable tool in forest management on many levels (Noceti and Brunetti 2024, Drew et al.

2022). This paper did not intend to create new models for assortment quality estimation, but rather to indicate the additional significant predictor of timber quality, and consequently timber value - tree crown defoliation degree.

5. Conclusions

Following the results of the conducted study, it can be concluded that:

- ⇒ on the researched sites, currently used single-entry volume tables could be used to calculate harvesting volumes in case of Norway spruce, while they can be improved in case of silver fir
- ⇒ declassification of produced logs was mostly influenced by presence of knots in the case of both researched species
- ⇒ average tree value is strongly influenced by the tree crown defoliation degree
- ⇒ additional research must be considered to develop new models for assortment structure prediction.

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Conflicts of Interest

»The authors declare no conflict of interest«

»The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results«.

Appendix A Tables and Figures

Table A1 Multiple regression parameters of determined tree gross volume

Tree species	Parameter	b^*	$SE\ of\ b^*$	b	$SE\ of\ b$	t	p	MR^2
Silver fir	<i>Intercept</i>	–	–	–4.60976	0.250345	–18.4137	<0.000001	0.9169
	DBH	0.652350	0.048608	0.09662	0.007199	13.4206	<0.000001	
	TH	0.368097	0.048608	0.09402	0.012415	7.5727	<0.000001	
Norway spruce	<i>Intercept</i>	–	–	–4.63440	0.263169	–17.6100	<0.000001	0.9094
	DBH	0.596675	0.045546	0.07960	0.006076	13.1005	<0.000001	
	TH	0.443500	0.045546	0.10990	0.011286	9.7374	<0.000001	

SE – standard error; M – multiple; DBH – diameter at breast height, cm; TH – tree height, m

Table A2 Multiple regression parameters of determined net HRN volume

Tree species	Parameter	b^*	$SE\ of\ b^*$	b	$SE\ of\ b$	t	p	MR^2
Silver fir	<i>Intercept</i>	–	–	–4.60976	0.250345	–18.4137	<0.000001	0.9158
	DBH	0.652350	0.048608	0.09662	0.007199	13.4206	<0.000001	
	TH	0.368097	0.048608	0.09402	0.012415	7.5727	<0.000001	
Norway spruce	<i>Intercept</i>	–	–	–4.63440	0.263169	–17.6100	<0.000001	0.9023
	DBH	0.596675	0.045546	0.07960	0.006076	13.1005	<0.000001	
	TH	0.443500	0.045546	0.10990	0.011286	9.7374	<0.000001	

SE – standard error; M – multiple; DBH – diameter at breast height, cm; TH – tree height, m

Table A3 Multiple regression parameters of determined net HRN EN volume

Tree species	Parameter	b^*	$SE\ of\ b^*$	b	$SE\ of\ b$	t	p	MR^2
Silver fir	<i>Intercept</i>	–	–	–3.91533	0.208486	–18.7799	<0.000001	0.9173
	DBH	0.634942	0.048467	0.07854	0.005995	13.1006	<0.000001	
	TH	0.387193	0.048467	0.08260	0.010339	7.9888	<0.000001	
Norway spruce	<i>Intercept</i>	–	–	–3.92384	0.232252	–16.8947	<0.000001	0.9022
	DBH	0.606288	0.047324	0.06870	0.005362	12.8114	<0.000001	
	TH	0.428989	0.047324	0.09029	0.009960	9.0649	<0.000001	

SE – standard error; M – multiple; DBH – diameter at breast height, cm; TH – tree height, m

Table A4 Multiple regression parameters of determined gross volume across different tree crown defoliation degrees

Tree species	TCDD	Parameter	b^*	$SE\ of\ b^*$	b	$SE\ of\ b$	t	p	MR^2
Silver fir	Healthy tree	<i>Intercept</i>	–	–	–4.51334	0.420268	–10.7392	<0.000001	0.9235
		DBH	0.695176	0.070398	0.09663	0.009785	9.8749	<0.000001	
		TH	0.367439	0.070398	0.08700	0.016668	5.2194	0.000024	
	Severely defoliated tree	<i>Intercept</i>	–	–	–4.42367	0.353714	–12.5063	<0.000001	0.9496
		DBH	0.546992	0.087539	0.08171	0.013077	6.2486	0.000003	
		TH	0.471854	0.087539	0.11242	0.020857	5.3902	0.000024	
	Dead tree	<i>Intercept</i>	–	–	–4.69831	0.483301	–9.72128	<0.000001	0.9099
		DBH	0.712059	0.096519	0.10823	0.014671	7.37739	<0.000001	
		TH	0.282948	0.096519	0.08128	0.027727	2.93152	0.006791	
Norway spruce	Healthy tree	<i>Intercept</i>	–	–	–4.81723	0.562963	–8.55693	<0.000001	0.8812
		DBH	0.432571	0.118519	0.06051	0.016578	3.64981	0.001336	
		TH	0.557364	0.118519	0.14439	0.030703	4.70276	0.000098	
	Severely defoliated tree	<i>Intercept</i>	–	–	–4.77548	0.424393	–11.2525	<0.000001	0.9248
		DBH	0.660630	0.063461	0.08398	0.008068	10.4099	<0.000001	
		TH	0.402215	0.063461	0.10869	0.017149	6.3379	0.000001	
	Dead tree	<i>Intercept</i>	–	–	–4.28695	0.358358	–11.9628	<0.000001	0.9477
		DBH	0.648060	0.062663	0.08464	0.008184	10.3421	<0.000001	
		TH	0.433363	0.062663	0.09104	0.013164	6.9158	0.000001	

TCDD – tree crown defoliation degree; SE – standard error; M – multiple; DBH – diameter at breast height, cm; TH – tree height, m

Table A5 Multiple regression parameters of determined net HRN volume across different tree crown defoliation degrees

Tree species	TCDD	Parameter	b^*	$SE\ of\ b^*$	b	$SE\ of\ b$	t	p	MR^2
Silver fir	Healthy tree	<i>Intercept</i>	–	–	–3.72575	0.332195	–11.2155	<0.000001	0.9292
		DBH	0.716117	0.067720	0.08179	0.007735	10.5747	<0.000001	
		TH	0.346389	0.067720	0.06739	0.013175	5.1150	0.000031	
	Severely defoliated tree	<i>Intercept</i>	–	–	–3.65475	0.339421	–10.7676	<0.000001	0.9326
		DBH	0.525952	0.101193	0.06522	0.012549	5.1975	0.000038	
		TH	0.483927	0.101193	0.09571	0.020014	4.7822	0.000100	
	Dead tree	<i>Intercept</i>	–	–	–4.12186	0.404344	–10.1940	<0.000001	0.9064
		DBH	0.600794	0.098347	0.07498	0.012274	6.1089	0.000002	
		TH	0.400261	0.098347	0.09441	0.023198	4.0699	0.000368	
Norway spruce	Healthy tree	<i>Intercept</i>	–	–	–3.99534	0.469875	–8.50299	<0.000001	0.8791
		DBH	0.437251	0.119559	0.05060	0.013837	3.65719	0.001312	
		TH	0.551648	0.119559	0.11824	0.025626	4.61402	0.000122	
	Severely defoliated tree	<i>Intercept</i>	–	–	–3.89801	0.361533	–10.7819	<0.000001	0.9199
		DBH	0.675123	0.065488	0.07085	0.006873	10.3091	<0.000001	
		TH	0.382768	0.065488	0.08539	0.014609	5.8449	0.000002	
	Dead tree	<i>Intercept</i>	–	–	–3.50113	0.344983	–10.1487	<0.000001	0.9291
		DBH	0.645856	0.072968	0.06973	0.007878	8.8512	<0.000001	
		TH	0.424463	0.072968	0.07372	0.012673	5.8171	0.000009	

TCDD – tree crown defoliation degree; SE – standard error; M – multiple; DBH – diameter at breast height, cm; TH – tree height, m

Table A6 Multiple regression parameters of determined net (HRN EN standard) volume across different tree crown defoliation degrees

Tree species	TCDD	Parameter	b^*	$SE\ of\ b^*$	b	$SE\ of\ b$	t	p	MR^2
Silver fir	Healthy tree	<i>Intercept</i>	–	–	–3.80810	0.345594	–11.0190	<0.000001	0.9268
		DBH	0.711526	0.068861	0.08314	0.008047	10.3328	<0.000001	
		TH	0.350300	0.068861	0.06972	0.013706	5.0871	0.000033	
	Severely defoliated tree	<i>Intercept</i>	–	–	–3.76842	0.342935	–10.9887	<0.000001	0.9348
		DBH	0.529380	0.099519	0.06744	0.012678	5.3194	0.000028	
		TH	0.481672	0.099519	0.09787	0.020222	4.8400	0.000088	
	Dead tree	<i>Intercept</i>	–	–	–4.16591	0.402097	–10.3605	<0.000001	0.9090
		DBH	0.594574	0.096988	0.07483	0.012206	6.1304	0.000002	
		TH	0.408206	0.096988	0.09709	0.023069	4.2088	0.000254	
Norway spruce	Healthy tree	<i>Intercept</i>	–	–	–4.10790	0.484984	–8.47016	<0.000001	0.8777
		DBH	0.430332	0.120225	0.05112	0.014282	3.57940	0.001588	
		TH	0.557626	0.120225	0.12268	0.026450	4.63819	0.000115	
	Severely defoliated tree	<i>Intercept</i>	–	–	–4.04336	0.372002	–10.8692	<0.000001	0.9202
		DBH	0.670366	0.065400	0.07249	0.007072	10.2502	<0.000001	
		TH	0.388318	0.065400	0.08925	0.015032	5.9376	0.000002	
	Dead tree	<i>Intercept</i>	–	–	–3.60763	0.341544	–10.5627	<0.000001	0.9340
		DBH	0.663952	0.070412	0.07355	0.007800	9.4295	<0.000001	
		TH	0.407266	0.070412	0.07257	0.012547	5.7840	0.000010	

TCDD – tree crown defoliation degree; SE – standard error; M – multiple; DBH – diameter at breast height, cm; TH – tree height, m

Table A7 Descriptive statistics of measured silver fir roundwood

TCDD	Quality class		VL	SLI	SLII	SLIII	PW
	Number of measured logs		3	20	41	22	30
Healthy fir tree	Length, m	<i>Average</i>	4.07	4.59	6.83	6.17	5.27
		<i>Standard deviation</i>	0.06	1.44	1.77	1.84	1.90
		<i>Minimum</i>	4.00	4.00	4.00	4.00	2.20
		<i>Maximum</i>	4.10	8.00	8.00	10.00	9.40
	Diameter, cm	<i>Average</i>	46.00	42.55	35.44	26.77	16.37
		<i>Standard deviation</i>	1.73	4.93	4.86	3.91	6.32
		<i>Minimum</i>	45.00	35.00	25.00	20.00	10.00
		<i>Maximum</i>	48.00	54.00	45.00	34.00	46.00
	Gross volume, m ³	<i>Average</i>	0.7883	0.7838	0.8232	0.4532	0.1540
		<i>Standard deviation</i>	0.0511	0.2171	0.2837	0.2100	0.1456
		<i>Minimum</i>	0.7467	0.4654	0.4215	0.1702	0.0214
		<i>Maximum</i>	0.8454	1.3387	1.5651	0.8670	0.8087
	Net HRN volume, m ³	<i>Average</i>	0.6764	0.6447	0.6724	0.3663	0.1272
		<i>Standard deviation</i>	0.0518	0.1876	0.2385	0.1808	0.1281
		<i>Minimum</i>	0.6521	0.3945	0.3485	0.1445	0.0173
		<i>Maximum</i>	0.7419	1.1222	1.3042	0.7445	0.6980

TCDD	Quality class		VL	SLI	SLII	SLIII	PW
	Number of measured logs			14	33	32	27
Severely defoliated fir tree	Length, m	<i>Average</i>	–	4.00	5.93	6.34	5.00
		<i>Standard deviation</i>	–	0.00	1.95	1.64	1.31
		<i>Minimum</i>	–	4.00	4.00	4.00	2.10
		<i>Maximum</i>	–	4.00	8.00	8.00	8.20
	Diameter, cm	<i>Average</i>	–	41.86	37.70	30.69	18.96
		<i>Standard deviation</i>	–	6.30	6.07	5.84	6.74
		<i>Minimum</i>	–	33.00	25.00	23.00	10.00
		<i>Maximum</i>	–	53.00	49.00	43.00	44.00
	Gross volume, m ³	<i>Average</i>	–	0.6817	0.8051	0.5978	0.1865
		<i>Standard deviation</i>	–	0.1947	0.3367	0.2855	0.1386
		<i>Minimum</i>	–	0.4117	0.3161	0.2299	0.0493
		<i>Maximum</i>	–	1.0235	1.5824	1.1713	0.5983
	Net HRN volume, m ³	<i>Average</i>	–	0.5617	0.6686	0.4906	0.1526
		<i>Standard deviation</i>	–	0.1750	0.2941	0.2459	0.1151
		<i>Minimum</i>	–	0.3507	0.2525	0.1855	0.0330
		<i>Maximum</i>	–	0.9045	1.3628	0.9796	0.5049
TCDD	Number of measured logs		–	–	6	30	68
Dead fir tree	Length, m	<i>Average</i>	–	–	5.33	6.48	6.64
		<i>Standard deviation</i>	–	–	2.07	1.82	2.10
		<i>Minimum</i>	–	–	4.00	4.00	2.10
		<i>Maximum</i>	–	–	8.00	8.25	10.20
	Diameter, cm	<i>Average</i>	–	–	42.17	35.53	30.94
		<i>Standard deviation</i>	–	–	3.66	6.57	9.98
		<i>Minimum</i>	–	–	38.00	23.00	12.00
		<i>Maximum</i>	–	–	47.00	53.00	53.00
	Gross volume, m ³	<i>Average</i>	–	–	0.8843	0.8127	0.6754
		<i>Standard deviation</i>	–	–	0.2605	0.3821	0.4652
		<i>Minimum</i>	–	–	0.5841	0.2634	0.0480
		<i>Maximum</i>	–	–	1.2573	1.6081	2.1138
	Net HRN volume, m ³	<i>Average</i>	–	–	0.7211	0.6677	0.5674
		<i>Standard deviation</i>	–	–	0.2062	0.3238	0.3980
		<i>Minimum</i>	–	–	0.4898	0.2119	0.0358
		<i>Maximum</i>	–	–	1.0430	1.3628	1.8091

TCDD – tree crown defoliation degree

Table A8 Descriptive statistics of measured Norway spruce roundwood

TCDD	Quality class		VL	SLI	SLII	SLIII	PW
	Number of measured logs		4	13	37	30	26
Healthy spruce tree	Length, m	<i>Average</i>	4.10	4.65	6.72	6.11	6.14
		<i>Standard deviation</i>	0.08	1.60	1.86	1.69	1.99
		<i>Minimum</i>	4.00	4.00	4.00	3.75	2.70
		<i>Maximum</i>	4.20	8.50	8.25	8.25	11.00
	Diameter, cm	<i>Average</i>	45.50	42.31	35.43	26.90	14.62
		<i>Standard deviation</i>	5.51	5.71	5.80	4.82	3.74
		<i>Minimum</i>	39.00	32.00	24.00	20.00	10.00
		<i>Maximum</i>	51.00	53.00	48.00	40.00	29.00
	Gross volume, m ³	<i>Average</i>	0.8095	0.8229	0.8020	0.4324	0.1361
		<i>Standard deviation</i>	0.1803	0.4135	0.2857	0.1850	0.0761
		<i>Minimum</i>	0.6167	0.3996	0.3281	0.1725	0.0443
		<i>Maximum</i>	1.0237	1.7865	1.6060	0.9579	0.3365
	Net HRN volume, m ³	<i>Average</i>	0.6758	0.6821	0.6566	0.3550	0.1086
		<i>Standard deviation</i>	0.1626	0.3596	0.2422	0.1569	0.0645
		<i>Minimum</i>	0.5017	0.3297	0.2708	0.1559	0.0322
		<i>Maximum</i>	0.8580	1.5463	1.3628	0.8245	0.2708
TCDD	Number of measured logs		–	14	33	32	27
Severely defoliated spruce tree	Length, m	<i>Average</i>	1	4.00	4.33	6.08	6.26
		<i>Standard deviation</i>	–	0.00	1.15	2.03	1.81
		<i>Minimum</i>	–	4.00	4.00	4.00	3.75
		<i>Maximum</i>	–	4.00	8.00	9.00	10.00
	Diameter, cm	<i>Average</i>	–	47.00	43.50	37.87	29.34
		<i>Standard deviation</i>	–	0.00	5.98	5.89	5.78
		<i>Minimum</i>	–	47.00	33.00	26.00	21.00
		<i>Maximum</i>	–	47.00	53.00	49.00	43.00
	Gross volume, m ³	<i>Average</i>	–	0.8444	0.7912	0.8098	0.5427
		<i>Standard deviation</i>	–	0.0000	0.2694	0.2718	0.2705
		<i>Minimum</i>	–	0.8444	0.4218	0.3156	0.1777
		<i>Maximum</i>	–	0.8444	1.4082	1.4756	1.1903
	Net HRN volume, m ³	<i>Average</i>	–	0.6936	0.6528	0.6665	0.4435
		<i>Standard deviation</i>	–	0.0000	0.2376	0.2320	0.2312
		<i>Minimum</i>	–	0.7113	0.3507	0.2708	0.1559
		<i>Maximum</i>	–	0.7113	1.2053	1.2468	0.9796

TCDD	Quality class		VL	SLI	SLII	SLIII	PW
	Number of measured logs		–	1	1	45	53
Dead spruce tree	Length, m	<i>Average</i>	–	4.00	4.00	6.16	6.86
		<i>Standard deviation</i>	–	0.00	0.00	1.84	2.56
		<i>Minimum</i>	–	4.00	4.00	3.75	2.10
		<i>Maximum</i>	–	4.00	4.00	8.25	13.50
	Diameter, cm	<i>Average</i>	–	44.00	41.00	37.56	24.49
		<i>Standard deviation</i>	–	0.00	0.00	6.80	9.46
		<i>Minimum</i>	–	44.00	41.00	23.00	9.00
		<i>Maximum</i>	–	44.00	41.00	50.00	49.00
	Gross volume, m ³	<i>Average</i>	–	0.7335	0.6704	0.8192	0.4386
		<i>Standard deviation</i>	–	0.0000	0.0000	0.2881	0.3254
		<i>Minimum</i>	–	0.7335	0.6704	0.2460	0.0397
		<i>Maximum</i>	–	0.7335	0.6704	1.4037	1.4021
	Net HRN volume, m ³	<i>Average</i>	–	0.6079	0.5278	0.6752	0.3662
		<i>Standard deviation</i>	–	0.0000	0.0000	0.2476	0.2772
		<i>Minimum</i>	–	0.6234	0.5413	0.1964	0.0317
		<i>Maximum</i>	–	0.6234	0.5413	1.1908	1.1763

TCDD – tree crown defoliation degree

Table A9 Parameters of Unequal N HSD post-hoc test of significant difference in average tree value between TCDD classes

Tree species	Tree crown defoliation degree	Dead trees	Severely defoliated trees	Healthy trees
Silver fir	Dead trees	–	0.000113	0.000113
	Severely defoliated trees	0.000113	–	0.025049
	Healthy trees	0.000113	0.025049	–
Norway spruce	Dead trees	–	0.000113	0.000112
	Severely defoliated trees	0.000113	–	0.057064
	Healthy trees	0.000112	0.057064	–

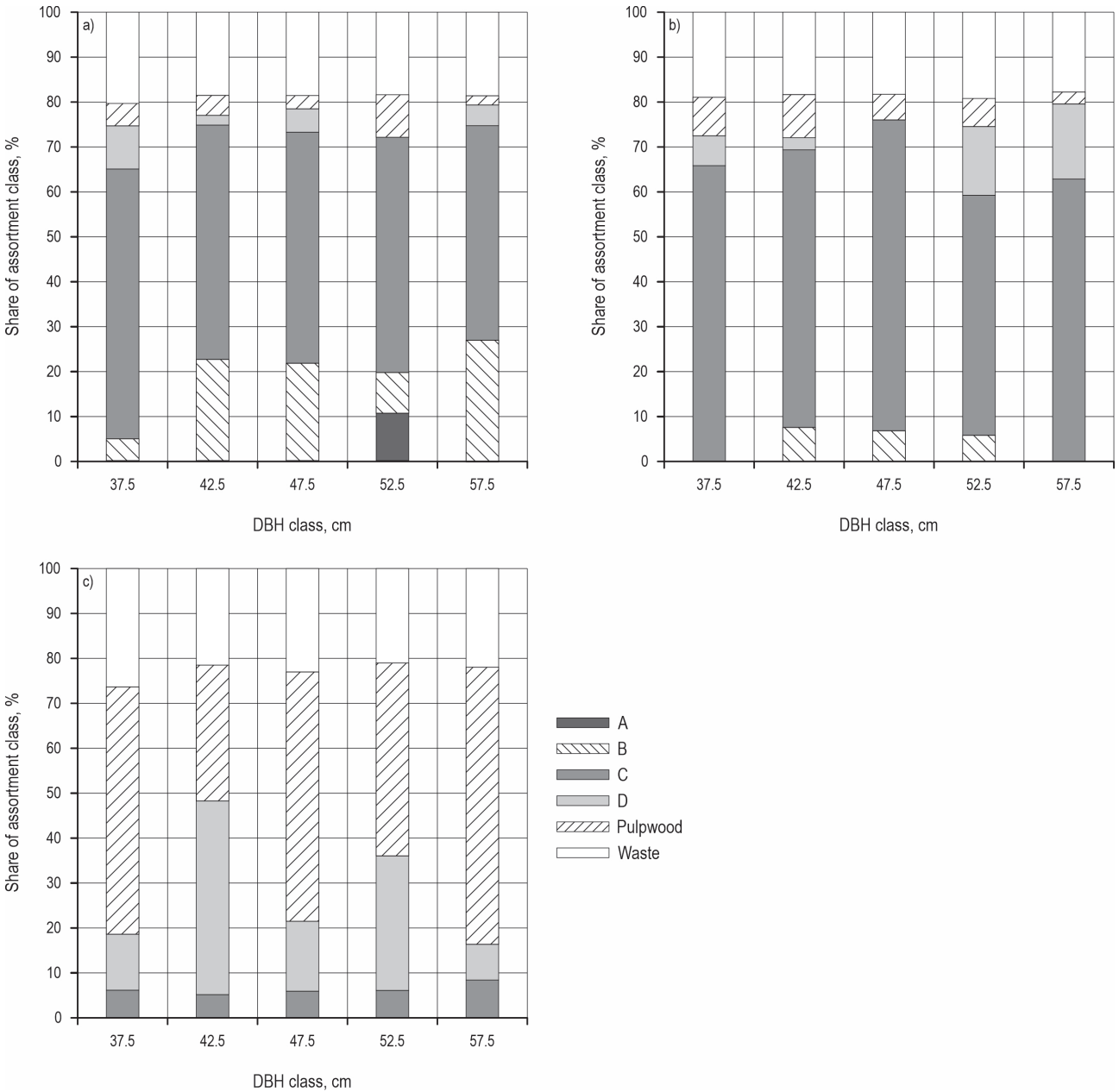


Fig. A1 Silver fir assortment structure according to HRN EN grading classes: a) for healthy fir trees, b) for severely defoliated fir trees, c) for dead fir trees

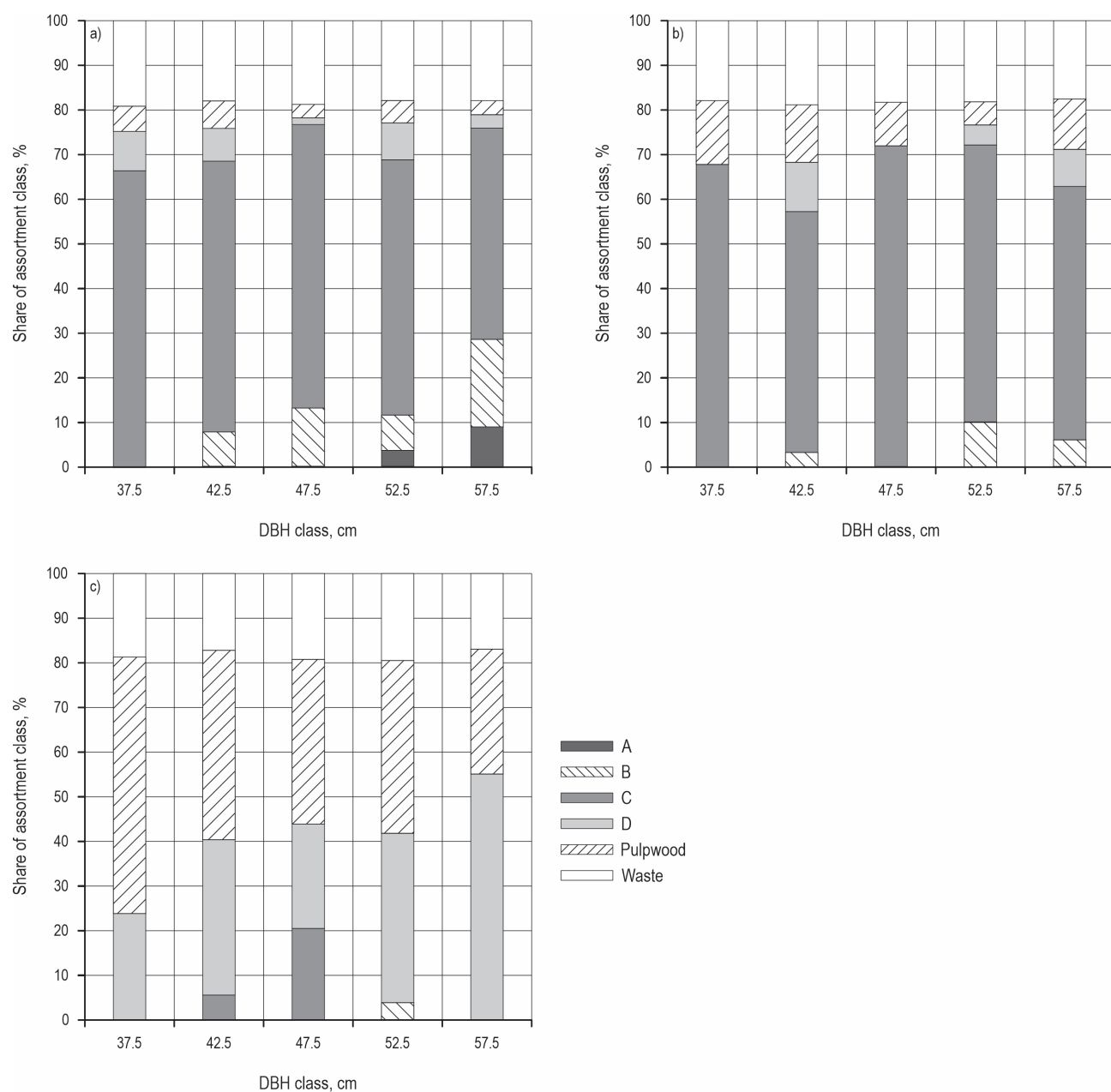


Fig. A2 Norway spruce assortment structure according to HRN EN grading classes: a) for healthy spruce trees, b) for severely defoliated spruce trees, c) for dead spruce trees

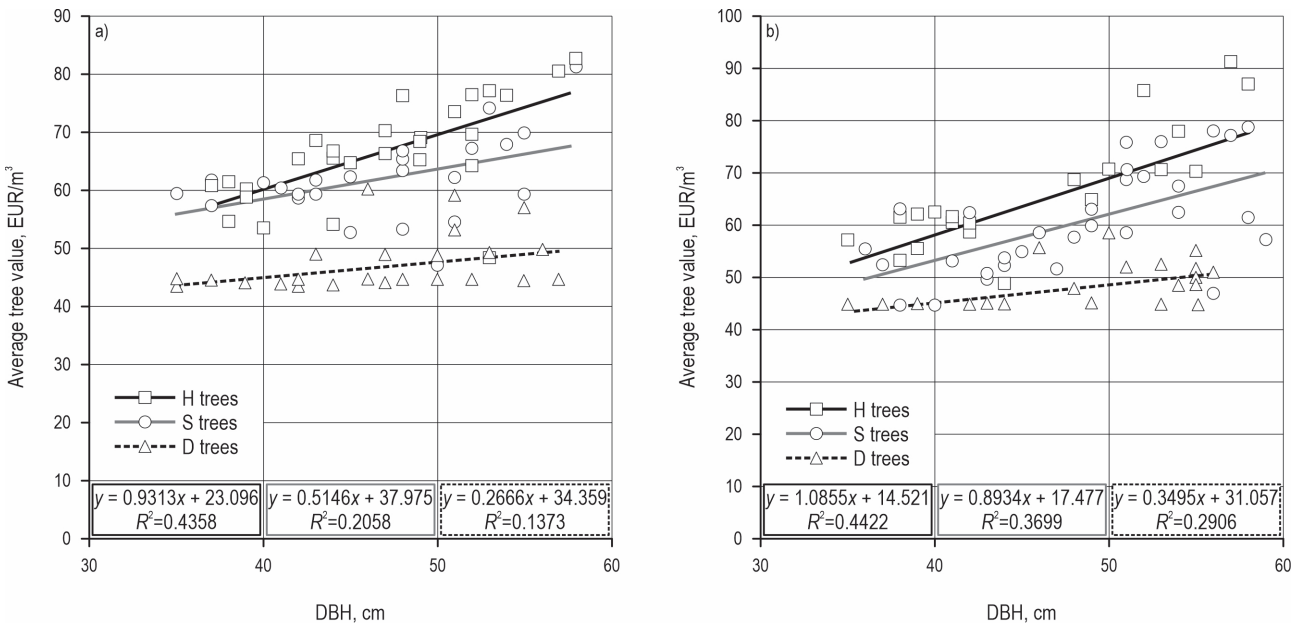


Fig. A3 Regression of average tree value (EUR/m³) and diameter at breast height (cm) for: a) silver fir, b) Norway spruce

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