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Energy Potential of Silver Fir and Norway Spruce Trees Affected by Dieback

Branko Ursić [1,*], Mihael Lovrinčević [1], Ivan Žarković [1], David Janeš [2], Andreja Đuka [1] and Dinko Vusić [1]

[1] University of Zagreb Faculty of Forestry and Wood Technology, Svetošimunska cesta 23, 10 000 Zagreb, Croatia; mlovrin@sumfak.unizg.hr (M.L.); izarkovi@sumfak.unizg.hr (I.Ž.); aduka@sumfak.unizg.hr (A.Đ.); dvusic@sumfak.unizg.hr (D.V.)
[2] Forest Administration Office Delnice, Croatian Forests Ltd., Supilova 32, 51 300 Delnice, Croatia; david.janes@hrsume.hr
* Correspondence: bursic@sumfak.unizg.hr

Abstract

This paper examines the energy potential of silver fir (*Abies alba* Mill) and Norway spruce (*Picea abies* (L.) Karst) trees across three tree crown defoliation degrees (TCDDs): healthy, severely defoliated (61–99%) and dead. The study was conducted in the area of the Forest Administration Delnice, Management Unit »Milanov vrh«, in the Republic of Croatia. Field measurements were conducted on 83 silver fir trees and 114 Norway spruce trees to determine the mass of live and dead branches per tree and to collect samples of wood, bark, main live and dead branches, and side live and dead branches (in total, 813) for further laboratory analyses. Further, differences in wood basic density, moisture content, ash content, net calorific value, and carbon, hydrogen, nitrogen, and sulfur content across TCDD classes were also determined. For both tree species, wood basic density across TCDDs decreased as follows: severely defoliated trees > healthy trees > dead trees. Regression analyses showed that the largest masses of branches occurred on healthy silver fir trees (R^2 = 0.48), followed by severely defoliated (R^2 = 0.41) and dead trees (R^2 = 0.46). The same trend in determined total branch mass per tree was observed for Norway spruce trees, where the coefficient of determination was highest for dead trees (R^2 = 0.72), followed by severely defoliated (R^2 = 0.69) and healthy (R^2 = 0.61) trees. A negative correlation between moisture content and TCDD class was observed for wood, bark, and live branches. The highest net calorific value was found for side live branches for both researched species, and only the net calorific value of side live branches of Norway spruce was statistically significantly different across TCDD classes. Overall, this study showed a negative impact of TCDD on the amount of available tree residues (branches) that could be utilized as a solid biofuel. Furthermore, the results of the laboratory analyses were ambiguous, increasing the complexity and heterogeneity of the wood material and underscoring the need for further investigation.

Keywords: branch biomass; wood density; elemental composition; moisture content; ash content; dead standing trees

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1. Introduction

Woodlands and forests cover more than 43.5% of the European Union's land area [1], representing a highly valuable and noteworthy resource. Social perception of forest ecosystems has changed over history, from the pre-industrial period, without any management

plan or strategic planning in place, to the post-industrial period, when the multifunctionality and sustainability of forests have emerged as two main principles of forest management [2]. Having accurate, impartial, and up-to-date information on the state of forests, their health, and their development is necessary given the numerous benefits forests provide [3]. In addition to wood production, erosion protection, water exchange, and local and global industry development [1,3], the high importance of forest ecosystems has been recognized in recent years through the many European policies promoting sustainable forest management, since forests are one of the crucial factors in the carbon cycle and reduce the negative impact of climate change [1,4]. Furthermore, among the other ecosystem services, stored carbon in forest ecosystems showed the greatest fluctuations due to its direct link with harvesting volume and growth increment [5].

According to the IPCC [6], above-ground biomass refers to all biomass of living vegetation, including both woody and herbaceous biomass above the soil; stems, stumps, branches, bark, seeds, and foliage. Furthermore, plant biomass from both above- and below-ground parts is the primary mechanism for CO_2 sequestration from the atmosphere [6]. As such, accurate biomass measurements and analyses have multiple uses in determining sequestration rates and carbon stocks, assessing potential climate change impacts, locating bio-energy processing plants, and mapping and planning fuel treatments [7]. Tree allometric equations are the most common method for assessing forest biomass based on basic tree components (e.g., tree diameter at breast height, tree height, or other dendrometric variables) [8,9]. Building biomass allometric equations requires sampling plan preparation based on the equation's purpose, field measurements and laboratory analyses, data formatting, model fitting and model validation [10]. For field measurements of biomass, a commonly used destructive method [11] involves tree felling and precise measurement of numerous tree characteristics.

Norway spruce (*Picea abies* (L.) Karsten) and silver fir (*Abies alba* Mill.) are ecologically and economically the most important coniferous tree species in Europe [12–14], as well as in Croatian forests. Both species together represent 78.9% of coniferous state-owned growing stock in Croatian forests [15]. Due to climate change, increased crown defoliation and mortality rates are reported in Norway spruce and silver fir [16–18]. According to the latest ICP Forests annual report for 2025, in Croatian forests, 45.79% of silver fir trees showed crown defoliation greater than 25%, which is 3.73% higher than the year before but significantly lower than in 2016, when 64.21% of silver fir trees were severely defoliated [19]. Monitoring of Norway spruce tree defoliation is not included in national programmes, and according to the latest available data, at the level of Croatian forests, 59.3% of Norway spruce trees showed over 25% crown defoliation, while in the region of Gorski Kotar, 96.2% of trees showed over 25% crown defoliation [20].

Allometric equations for Norway spruce have mostly been developed to determine tree height [21,22], crown height [23–25], crown width [26], height of the first dead branch and whorl [27,28], branch length [29], estimation of dry stem, live and dead branches, foliage mass [30–33], and total above-ground biomass [34–36]. In the case of silver fir, very few allometric equations have been developed [37]. Lately, allometric equations for silver fir have mostly been developed to estimate above-ground biomass [38,39], bark thickness [40], and carbon and nutrient content [41]. For both fir and spruce tree species, allometric equations were developed by measuring healthy trees [21–41]. As such, they are not suitable for trees affected by dieback. Namely, during a stand rotation, various natural influences can appear (windbreaks, snowbreaks, new diseases, etc.) that can significantly change the conditions in which stands grow. Lately, numerous studies have focused on dieback-affected forests as one of the negative consequences of climate change [42,43], as well as on disturbances in the wood supply chain due to the increased share of salvage

logging [44]. Tree decline is characterized by reduced growth, shortened internodes, yellowing and loss of foliage, dieback of twigs and branches, etc. [45]. Thus, a first indicator of tree decline is tree crown defoliation [46]. Furthermore, losses of above-ground biomass under tree decline can be significant [47], further increasing the uncertainty of allometric equations developed for healthy trees.

The relationship between the assortment structure and the degree of tree crown defoliation over the last two decades in Croatia was examined for pedunculate oak (*Quercus robur* L.), narrow-leaved ash (*Fraxinus angustifolia* Vahl), silver fir, and Norway spruce [48–52]. The degree of tree crown defoliation is mostly used to improve mortality models [53] and growth rate models [54], as an indicator of tree health and vigour [55], and as an indicator of air contamination [56].

Many studies emphasise that allometric biomass models are species- and site-specific [39,57–59], while the relationship between tree crown defoliation degree and the quantity and quality of above-ground biomass has rarely been researched. This study aimed to determine whether the dieback of silver fir and Norway spruce influenced the amount and quality (as solid biofuel) of unprocessed tree parts.

2. Materials and Methods

2.1. Sample Preparation

Research was conducted in the summer periods over three years (2022–2024) in four subcompartments located in the Forest Administration Delnice area, Management Unit »Milanov vrh« (φ 45°36′45.7″ N; λ 14°33′03.9″ E), where a combination of selective and salvage felling of silver fir and Norway spruce was performed. Tree marking was performed by forestry engineers from the company »Croatian Forests« Ltd., Zagreb, Croatia, after which sample trees were randomly chosen based on the diameter at breast height (DBH) and TCDD. To determine DBH, two perpendicular diameters at 1.3 m above ground were measured from the upper side of the slope. The ICP guidelines for visual assessment of crown condition and damaging agents [60] were used to estimate crown area visually without needles. The following classes were used for the classification: healthy tree (H) if the 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. After sample trees were chosen, they were cut down and processed into logs, after which the quality and quantity of produced logs, as well as the length of the unprocessed crown, were determined. For the full description of tree sampling and results of the quality and quantity of measured logs, see Ursić and Vusić [52]. This paper is a continuation of the aforementioned research and addresses the energy potential of produced pulpwood and unprocessed tree biomass from healthy, severely defoliated, and dead silver fir and Norway spruce trees.

2.2. Sampling Procedure

The sampling procedures for branch quantity determination and tree part quality determination are shown in Figure 1. After the logs were produced, the referenced live and dead branches were found for each tree. Referenced branches were further divided into the main branch and side branches to determine the mass ratio between them, after which they were sampled for further laboratory analyses and calculation of the branch biomass. Additionally, a sample of the bark and a debarked 5 cm wide disc were taken from the thicker side of the last pulpwood log in the tree. The initial mass of samples was determined in the field using a KERN EMB-S balance (KERN & SOHN GmbH, Balingen-Frommern, Germany). For the discs, two perpendicular diameters were measured with an accuracy of 0.1 cm, and four disc heights and four bark thicknesses were measured with an accuracy of 0.1 mm. After sampling was completed, the total mass of live and dead branches per

sample tree was determined using an industrial hanging scale, the ATP OCS-150 (ATP Instrumentation Ltd., Leicestershire, UK).



Figure 1. Example of field branch mass determination, and sampling of researched tree parts.

2.3. Laboratory Analyses

The laboratory analyses started with the determination of total moisture content in collected samples according to the HRN EN ISO 18134-2 standard [61]. Figure 2 shows the flowchart of sample collection, preparation, analysis, and result processing. Generally, samples were dried at 105 °C in a heating chamber until constant mass was reached. For all samples, oven-dry mass was recorded using a Kern 440-49A balance (KERN & SOHN GmbH, Balingen-Frommern, Germany). For the determination of ash, carbon, hydrogen, nitrogen, and sulfur content, as well as for calorific value determination, samples were prepared in a cutting mill to reduce the nominal particle size to below 0.50 mm. A list of standards and equipment used for all laboratory analyses is provided in Table A1.

2.4. Data Processing

Data processing started with the creation of the following data sets: wood basic density; live and dead branch biomass per sampled tree; and moisture, ash, carbon, sulfur, and nitrogen content and calorific value for sampled tree parts. All data sets were created in MS Excel 2412 software.

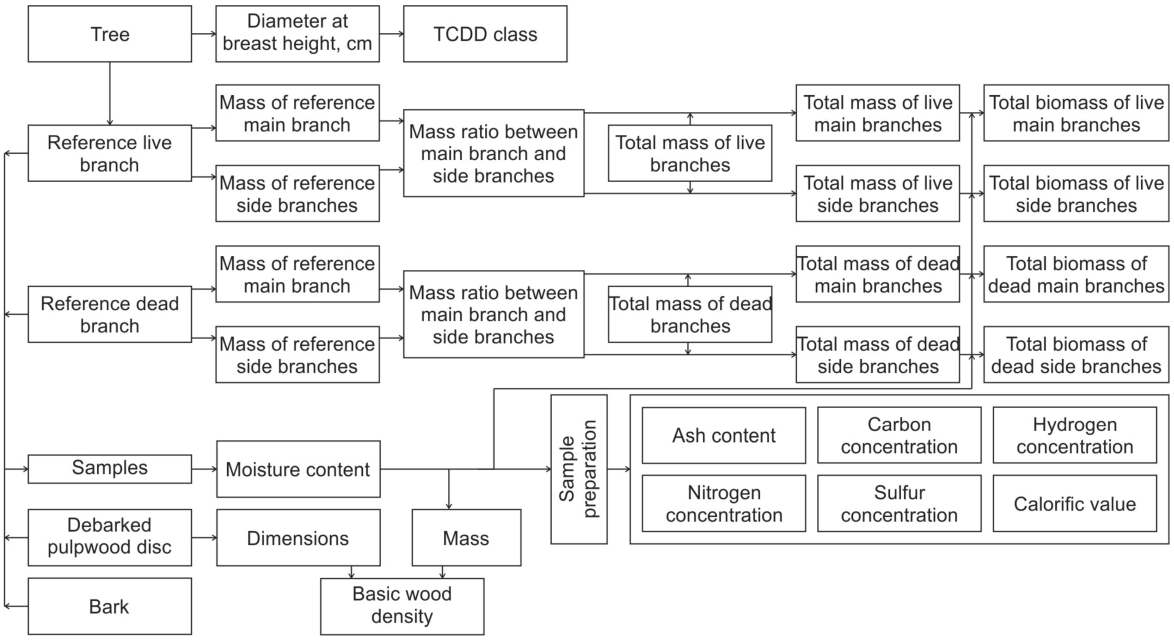

Figure 2. Flowchart of laboratory analyses and data processing.

A data set for wood basic density was created based on the calculated wood basic density (kg/m^3) for each sampled tree. The dimensions of each sampled wood disc (measured in the field) and the oven-dry mass were used to calculate wood basic density according to the following equation:

$$BD = \frac{m_{OD}}{\frac{d^2 * 3.14}{4{,}000{,}000} * h} \quad (1)$$

where BD is wood basic density (kg/m^3), m_{OD} is oven-dry pulpwood disc mass (kg), d is disc diameter (cm) and h is disc height (cm).

To create a data set of branch biomass per tree, firstly, the green mass (determined in the field) of the reference (live and dead) branches and the mass of their main and side branches were used to calculate the share of main and side branches in the total mass of the reference branch using the following equation:

$$\%_{XYB} = \frac{m_{RXYB}}{m_{RYB}} * 100 \quad (2)$$

where $\%_{XYB}$ is the share of observed type of branch (%), m_{RXYB} is the mass of the reference main/side branch (kg), m_{RYB} is the total mass of the reference branch (kg), $_X$ defines whether the observed branch is main or side, and $_Y$ defines whether the observed branch is alive or dead.

Further, the total mass of live and dead branches per tree (determined in the field) was divided into the mass of main live and dead branches and the mass of side live and dead branches using the following equation:

$$m_{XYB} = m_{TYB} * \%_{XYB}/100 \quad (3)$$

where m_{XYB} is the mass of observed type of branches in the tree (kg), m_{TYB} is the total mass of dead or live branches in the tree (kg), $\%_{XYB}$ is the share of observed type of branches (%), $_X$ defines whether the observed branch is main or side, and $_Y$ defines whether the observed branch is alive or dead.

Using the determined moisture content, the total branch biomass (oven-dry mass) per tree was calculated according to the following equation:

$$TBB = m_{MLB} - \left(m_{MLB} * \frac{MC_{MLB}}{100}\right) + m_{SLB} - \left(m_{SLB} * \frac{MC_{SLB}}{100}\right) + m_{MDB} - \left(m_{MDB} * \frac{MC_{MDB}}{100}\right) + m_{SDB} - \left(m_{SDB} * \frac{MC_{SDB}}{100}\right) \quad (4)$$

where *TBB* is total branch biomass (kg), *MC* is moisture content (%), m is branch mass (kg), $_{MLB}$ defines main live branches, $_{SLB}$ defines side live branches, $_{MDB}$ defines main dead branches, and $_{SDB}$ defines side dead branches.

Following that, the created data set contained data on tree number, tree species, TCDD class, diameter at breast height (cm), and branch biomass (kg). The average branch biomass per tree was calculated for each DBH class and TCDD class, after which a reduction factor in branch biomass of severely and defoliated trees was calculated.

The results of the laboratory analyses were used to create a data set of the ash content, elemental composition, and calorific value for each sampled tree part. All laboratory results are expressed on a dry basis. Further, net calorific value was calculated using Equation (4) according to the HRN EN ISO 18125:2017 standard [62]:

$$q_{p,\,net,\,d} = q_{V,\,gr,\,d} - 212.2 * w(H)_d - 0.8 * [w(O)_d + w(N)_d] \quad (5)$$

where $q_{p,net,d}$ is the net calorific value for a dry sample (J/g), $q_{V,gr,d}$ is the gross calorific value for a dry sample (J/g), $w(H)_d$ is the hydrogen share in a dry sample (%) and $w(O)_d$ is the oxygen share in a dry sample.

2.5. Data Analyses

MS Excel 2412 was used for regression analysis to determine the correlation between DBH and branch biomass among TCDD classes for both researched tree species and for all measured trees.

Statistical analyses were performed using TIBCO Statistica 14.0.0.15. Analysis of variance and Scheffe's post hoc test were employed to determine whether TCDD class has a statistically significant influence on (a) branch biomass in DBH classes 37.5–57.5 cm, because in those DBH classes at least two trees were measured; (b) wood basic density; (c) ash content; (d) elemental composition; and (e) calorific value. For all statistical tests, statistical significance was accepted at $\alpha < 0.05$.

3. Results and Discussion

3.1. Discs

In total, 77 discs of silver fir and 113 discs of Norway spruce were collected and analyzed. Average disc diameter, bark thickness, and wood basic density are shown in Table A2. Since most mechanical properties correlate with wood density, it represents an important physical property [63]. Generally, Norway spruce had greater wood basic density than silver fir. The highest average wood basic density was found in severely defoliated Norway spruce trees (417.51 kg/m^3), followed by healthy (408.33 kg/m^3) and dead trees (385.49 kg/m^3). The average wood density of spruce wood is highly correlated with the ratio between early (300 kg/m^3) and late (1140 kg/m^3) wood [64–66], which means that basic density increases with decreasing width of growth rings [67–69]. In addition, the wood basic density of spruce trees slowly decreases with tree height but increases near the tree top [69,70]. Further, a study of tree-ring wood density in European mountain forests reported that the late and mean wood density of silver fir decreased by 16.8% and 11.0%, respectively, while the late and mean wood density of Norway spruce decreased by 16.1%

and 7.2%, respectively, in the period between 1901 and 2016 [71]. The determined wood basic density of Norway spruce in our research was in the range of previous studies, which reported that the wood basic density of Norway spruce was between 373 and 331 kg/m^3 in the northern part of Norway [69], 325–425 kg/m^3 in Denmark [68], and 330–375 kg/m^3 in the Czech Republic [72]. In the case of silver fir, the greatest average nominal wood density was also determined for severely defoliated trees (387.38 kg/m^3), followed by healthy trees (386.25 kg/m^3) and dead trees (355.65 kg/m^3). For silver fir, changes in basic density along tree height were also reported, where basic density at breast height was statistically significantly higher than the mean basic density of the stem [73]. Additionally, a different basic density was observed between the knots (685 kg/m^3) and stem wood (374 kg/m^3) of silver fir [74]. Further, dead fir and spruce trees had a higher share of rot than healthy and severely defoliated trees [52], which can significantly decrease wood density [75].

Analysis of variance showed statistically significant differences in wood basic density among TCDD classes for both researched tree species (Figure 3). Further, Scheffe's post hoc test showed that in the case of silver fir, dead trees had statistically significantly lower basic density than healthy and severely defoliated trees, while in the case of Norway spruce, wood basic density was statistically significantly lower compared to the basic density of severely defoliated trees (Table A3). Severely defoliated trees of both tree species had greater nominal wood density (2.25% for Norway spruce and 0.29% for silver fir) than healthy trees, probably because of thinner growth rings caused by tree decline and producing a higher proportion of latewood. Further, wood decomposition can have a negative impact on wood density. Mouldy and soft wood can have up to 36% lower wood density than dead trees [76]. Our results showed 5.59% and 7.92% lower wood density (compared to the healthy trees) of dead Norway spruce and silver fir trees, respectively. The study results support the idea of including the TCDD class as an indicator of wood basic density and overall tree quality. As well as a physical property indicator, wood density is highly important for carbon stock calculation because it is expressed as the mass of stored carbon, which can be easily calculated from carbon content, wood density, and wood volume.

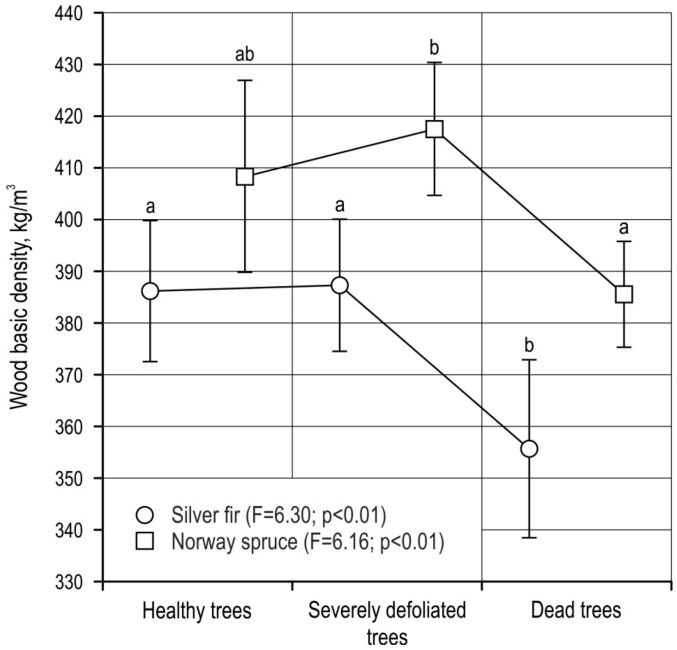

Figure 3. Differences in wood basic density between tree crown defoliation degrees (vertical bars denote a confidence interval of 0.95; different letters denote homogenous groups at the tree species level).

3.2. Branch Biomass

In total, 83 silver fir and 114 Norway spruce trees were sampled and measured to determine total branch mass. In terms of green mass, the total measured branch mass was 30,913 kg for silver fir and 39,263 kg for Norway spruce. To eliminate the influence of differences in moisture content between TCDD classes and trees, further analysis was conducted using oven-dry mass (branch biomass). Further, regression equations (Figure 4 and Table A4) were established to determine the relationships between DBH and total branch biomass for the investigated species. Generally, a higher coefficient of determination (over 0.60) was observed for Norway spruce, whereas for silver fir it ranged from 0.41 to 0.48. The highest coefficient of determination was observed for Norway spruce dead trees, followed by severely defoliated and healthy trees (Table A4). Average branch biomass per tree was positively correlated with DBH class and negatively correlated with TCDD class for both investigated tree species.

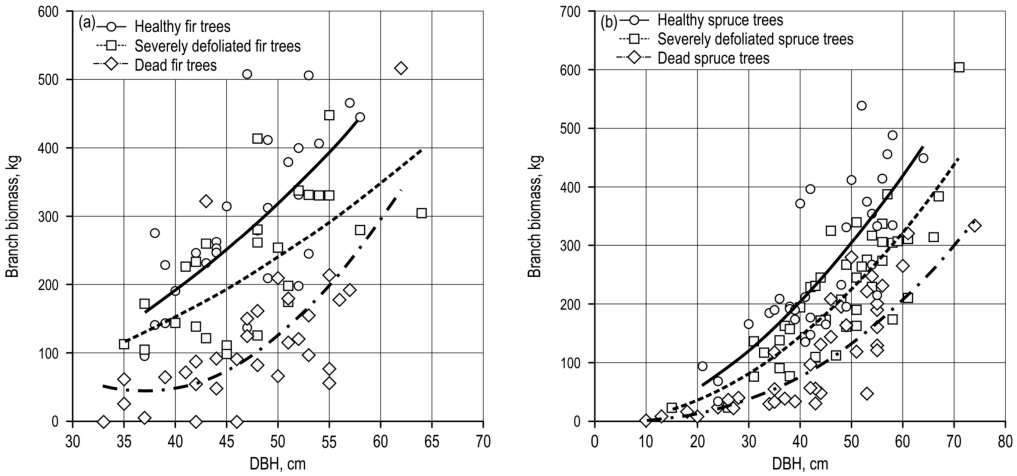

Figure 4. Branch biomass (oven-dry mass) among TCDD and DBH classes for (**a**) silver fir and (**b**) Norway spruce.

Analysis of variance showed statistically significant differences in branch biomass between TCDD classes, except for Norway spruce in DBH class 47.5 (Table A5). Norway spruce trees in DBH class 47.5 had very similar average branch biomass regardless of TCDD class (Figure A1). Further, Scheffe's post hoc test (Table A6) showed that D trees had statistically significantly different (lower) branch biomass compared to the H trees for both investigated tree species (except for DBH class 47.5 in the case of Norway spruce). For DBH class 47.5 and below, dead silver fir trees had statistically significantly greater branch biomass than healthy trees. In contrast, trees in DBH classes 52.5 and 57.5 had statistically significantly different branch biomass than healthy and severely defoliated fir trees. In the case of Norway spruce, except for the DBH class 47.5, healthy trees had statistically significantly greater branch biomass.

The results of this study showed up to 71% and 81% reductions in branch biomass for Norway spruce and silver fir dead trees, respectively (Table 1). In the case of severely defoliated tree branches, biomass reduction was up to 31% for silver fir and 37% for Norway spruce. Reduced above-ground biomass or tree structural loss has multiple significant influences. Firstly, it influences the total amount of available biomass that can be used for different purposes, e.g., branches and bark, which can be used as solid biofuel [77]. Secondly, the total amount of carbon stored in standing trees decreases due to structural loss [78]. Further, incorporating the density reduction factor and structural loss adjustment factor can reduce estimated top and branch biomass by up to 78% [78]. Moreover, it has been reported that the C content of standing dead trees can be reduced by almost 60% due to reduced tree structure [79].

Table 1. Branch biomass reduction factors among TCDD and DBH classes.

DBH	Silver Fir			Norway Spruce		
	Healthy Trees	Severely Defoliated Trees	Dead Trees	Healthy Trees	Severely Defoliated Trees	Dead Trees
37.5	1	0.74	0.19	1	0.65	0.29
42.5	1	0.79	0.41	1	0.79	0.29
47.5	1	0.69	0.33	1	0.90	0.77
52.5	1	0.77	0.38	1	0.65	0.47
57.5	1	0.77	0.32	1	0.80	0.46

3.3. Results of Laboratory Analysis

The number of samples tested in this study by tree species, TCDD class, and analysis is shown in Table A7. In total, 813 samples were tested to determine moisture content, ash content, elemental composition and calorific value.

3.3.1. Moisture Content

Analysis of moisture content was done on 813 samples (wood, bark, and live and dead branches). The importance of moisture content is reflected in a reduced heating value [80] and in the added weight of the fuel, increasing both transport and overall supply chain costs [81]. In terms of solid biofuels, the lower moisture content of dead trees makes them better suited as solid biofuels than severely defoliated and healthy trees if they are used in the short time after felling. On the other hand, this solid biofuel property can be easily managed through forest biomass seasoning, which is well documented [82,83]. Differences in moisture content among TCDD classes were not statistically tested due to the research limitations. Namely, research was conducted over three years, during which environmental conditions (e.g., precipitation) were likely not the same. Furthermore, sampling was not always conducted on the same day when felling was performed, during which time the moisture could have evaporated. Despite this, on average, healthy trees had higher moisture content than severely defoliated and dead trees (Figure 5).

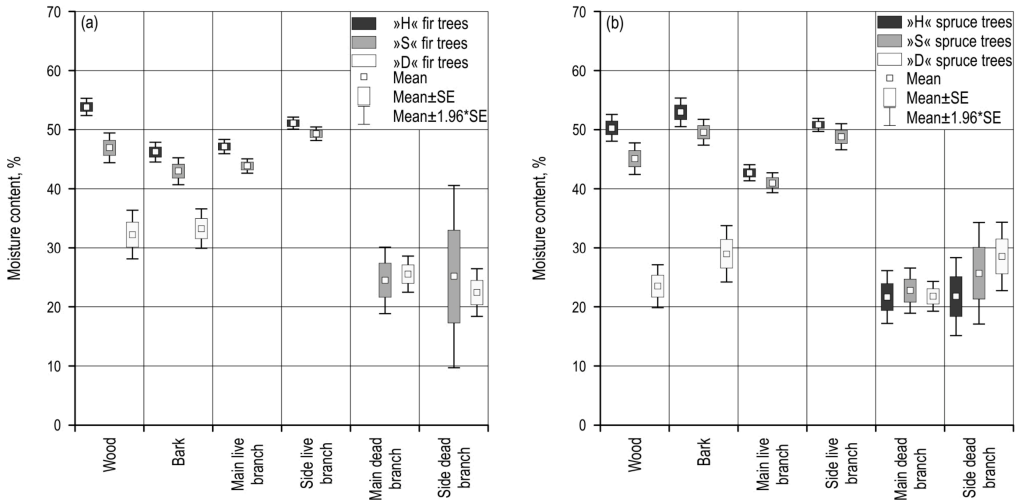

Figure 5. Moisture content among tree parts and TCDD classes for (**a**) silver fir and (**b**) Norway spruce. (»H« healthy trees, »S« severely defoliated trees, »D« dead trees).

The highest average moisture content was found for healthy silver fir wood (53.86% ± 3.87%), while the wood of healthy Norway spruce trees had slightly lower moisture content (50.34% ± 6.51%). Moisture content in the wood of severely defoliated trees was quite similar for both researched species, 46.94% ± 6.43% for silver fir and 45.13% ± 8.93% for Norway spruce, while the wood of dead Norway spruce trees had notably lower moisture content (23.55% ± 11.37%) than the wood of dead silver fir trees (32.26% ± 11.57%). In contrast to the wood samples, the bark of Norway spruce trees, on average, had higher moisture content than wood, while fir bark had lower average moisture content than fir wood samples. Furthermore, the bark of dead Norway spruce trees had the lowest moisture content (29.04% ± 14.64%), followed by severely defoliated trees (49.60% ± 7.30%) and healthy trees (52.95% ± 6.97%). On the species level, the bark of dead silver fir had a higher moisture content (33.30% ± 9.00%) than the bark of dead spruce trees, while the bark of severely defoliated (42.98% ± 5.82%) and healthy (46.22% ± 4.43%) fir trees had lower average moisture content than the bark of severely defoliated and healthy spruce trees. For both researched tree species, side branches had greater moisture content than main branches, and branches from healthy trees had greater moisture content than those from severely defoliated trees (Figure 5).

3.3.2. Ash Content

Ash is a by-product of solid biofuel combustion, appearing as bottom or fly ash that needs to be removed from the furnace [84], and it has an inorganic origin. For both species, the lowest ash content was found in wood of healthy trees, 0.43% ± 0.14% for silver fir and 0.35% ± 0.07% for Norway spruce (Table A8). The results of this study regarding ash content in wood correspond with a previously reported range of ash content for clean woody biomass (0.2 and 1.0%) [85] and typical variation in ash content of coniferous wood (0.1–1.0%) [77], with ash contents of 0.38% [86] and 0.3% [87] reported for pure Norway spruce wood. Notably higher ash content, but still in the expected range, was found for bark regardless of tree species and TCDD classes. For the bark, the highest ash content was found in bark samples of dead Norway spruce trees (4.94 ± 1.41%), followed by bark taken from dead silver fir trees (4.35% ± 0.98%). The average ash content in the bark of healthy and severely defoliated Norway spruce trees (3.78%) was close to the previously reported 3.88% [86]. Previous studies of ash content in silver fir bark reported an influence of tree age (ash content ranged from 2.67% for 100-year-old fir trees to 4.46% for 40-year-old fir trees) [88] and sampling height (ash content ranged from 1.8% at the tree bottom to 2.5% at the tree top) with the emphasis that the ash content in the bark of silver fir does not vary significantly with a mean value of 2.2% [89]. Generally, the average ash content in bark was in the expected range (<1–5%) for clean coniferous trees' bark [77], regardless of TCDD class. The average ash content in main live branches (regardless of TCDD class) was 2.28% ± 0.50% for Norway spruce and 2.44% ± 0.44% for silver fir. Generally, the ash content of the main Norway spruce branches (2.14% ± 0.72%) matched the previously reported 2.12% [90]. Significantly higher and less desirable ash content was found for side live branches for both species (5.54% ± 0.94% for silver fir and 4.48% ± 0.66% for Norway spruce), regardless of TCDD class. The high ash content of side live branches can be reduced by seasoning branches until the needles fall off, since individual silver fir branches can have ash content up to 4.97% [88].

Generally, the average ash content in the wood, side live branches, main and side dead branches, and bark of silver fir trees was positively correlated with TCDD class (Table A8). For Norway spruce, the average ash content was positively correlated with TCDD class for main and side live branches, side dead branches, and bark. Analysis of variance (Table 2) showed that the bark of silver fir trees and bark and main live branches had statistically significantly different ash content between TCDD classes. For both species, the bark of dead

trees had statistically significantly higher ash content than healthy and severely defoliated trees. In contrast, in the case of Norway spruce, the main live branches of healthy trees had statistically significantly lower ash content than severely defoliated trees (Table A9).

Table 2. Analysis of variance in ash content between TCDD classes among all tree parts.

Tree Species	Tree Part	SS Effect	Df Effect	MS Effect	SS Error	Df Error	MS Error	F	*p*
Silver fir	Wood	0.2167	2	0.1084	3.0033	79	0.0380	2.8506	0.0638
	Bark	7.5779	2	3.7890	50.7059	77	0.6585	5.7538	0.0047
	Main live branches	0.0051	1	0.0051	13.8218	50	0.2764	0.0185	0.8923
	Side live branches	0.0047	1	0.0047	45.2846	50	0.9057	0.0052	0.9431
	Main dead branches	0.0199	1	0.0199	16.3625	32	0.5113	0.0388	0.8450
	Side dead branches	0.3457	1	0.3457	5.0867	19	0.2677	1.2913	0.2699
Norway spruce	Wood	0.0454	2	0.0227	1.2652	110	0.0115	1.9738	0.1438
	Bark	38.5459	2	19.2730	140.5451	108	1.3013	14.8101	<0.0001
	Main live branches	2.1587	1	2.1587	16.7817	74	0.2268	9.5191	0.0029
	Side live branches	0.0222	1	0.0222	32.2978	73	0.4424	0.0501	0.8235
	Main dead branches	3.3782	2	1.6891	50.8517	69	0.7370	2.2919	0.1087
	Side dead branches	3.0094	2	1.5047	24.0970	41	0.5877	2.5602	0.0896

3.3.3. Elemental Composition

The main combustible elements in fuel are carbon and hydrogen, while the contributions of nitrogen and sulfur in combustion are low but important in evaluating fuel suitability from an environmental point of view [88]. The results of this study showed that the wood of both tree species had the lowest carbon content among other tree parts, and that Norway spruce wood generally had lower carbon content than silver fir wood. In the case of silver fir, carbon content was positively correlated with TCDD class. Namely, the wood of dead fir trees had a higher carbon content (51.55% ± 0.42%) than that of severely defoliated (51.44% ± 0.37%) or healthy trees (51.36% ± 0.33%). In the case of Norway spruce, severely defoliated trees had the highest carbon content in wood (51.19 ± 0.44%), followed by healthy trees (51.17% ± 0.18%) and dead trees (51.07% ± 0.31%). The results of this study showed slightly higher carbon content than previously reported, 51.10% and 50.90% for silver fir and Norway spruce wood, respectively [41], which can be explained by the fact that the content of nutrients may show an increasing trend with the increasing height of the sampling point [91]. Namely, in this research, wood samples were taken from pulpwood, an assortment commonly produced from the upper parts of trees, while in the mentioned research, sampling was done at a height of 1.3 m above the ground. For both researched tree species, the highest average content of carbon was found for side dead branches of dead trees (53.83% ± 0.89% for silver fir and 53.35% ± 0.72% for Norway spruce), followed by side live branches that included needles (Figure A2). Only spruce bark

had a higher carbon content than silver fir samples. This study confirmed the previously reported trend of carbon content among tree parts, with needles having the highest carbon content, followed by bark and wood [41]. Analysis of variance showed a statistically significant influence of TCDD class on carbon content only for Norway spruce side dead branches (Table A10). Further, Scheffe's test (Table A11) showed that side dead branches of healthy spruce trees have statistically significantly lower carbon content (52.12% ± 0.51%) than severely defoliated (53.11% ± 0.95%) and dead trees (53.35% ± 0.72%). Several studies have already reported increased carbon content by increasing wood decay class [92,93].

The hydrogen contents in our research ranged from 5.04% ± 0.38% for the bark of dead spruce trees to 6.24% ± 0.29% for the side live branches of severely defoliated spruce trees. Side live branches generally had the highest hydrogen content (Figure A3). Hydrogen content in the main dead branches of Norway spruce trees and bark of both tree species differed significantly between TCDD classes (Table A12). According to Scheffe's post hoc test (Table A13), the bark of dead fir trees had a significantly lower hydrogen content (5.39% ± 0.33%) than that of the bark of severely defoliated trees (5.79% ± 0.28%) and healthy trees (5.92% ± 0.22%). This trend was also seen for Norway spruce bark: dead trees had the lowest hydrogen content (5.04% ± 0.38%), followed by severely defoliated trees (5.47% ± 0.28%) and healthy trees (5.59% ± 0.36%). An unexpected trend was observed for the main dead branches of Norway spruce: dead main branches of dead trees had significantly higher hydrogen content (5.82% ± 0.17%) than those of severely defoliated trees (5.70% ± 0.14%), though this was not statistically different from healthy trees (5.77% ± 0.14%).

The nitrogen and sulfur contents are expected to be quite low. According to the HRN EN ISO 17225-1 [77], typical nitrogen content for virgin wood materials is below 0.5%, and for virgin bark material it is below 0.9%. Our study showed that the nitrogen content (Figure A4) for the wood of both researched species was below 0.23%, whereas that of the bark ranged from 0.40% ± 0.11% to 0.61% ± 0.23%. Generally, the lowest nitrogen content was in wood, followed by main branches, bark, and side branches. Nitrogen content below 0.60% is considered unproblematic for combustion [94]. In those terms, the bark of dead spruce trees and the main and side live and dead branches (regardless of tree species and TCDD class) could be considered inappropriate solid biofuel if used alone. Mixing them with material with lower nitrogen content can lower the nitrogen content to below the recommended 0.60%.

Analysis of variance showed that only the bark of spruce trees had a statistically significant difference in nitrogen content between TCDD classes (Table A14). Further, Scheffe's post hoc test (Table A15) showed that the bark of dead spruce trees (0.61% ± 0.23%) had statistically significantly higher nitrogen content than bark of healthy (0.49% ± 0.12%) and severely defoliated (0.44% ± 0.10%) spruce trees.

According to the HRN EN ISO 17225-1 standard [77], sulfur content is expected to be: <0.02% for coniferous wood, <0.05 for coniferous bark, and <0.06% for logging residues. Our study showed that sulfur content (Figure A5) was below 0.001% in spruce wood regardless of TCDD class, whereas sulfur in fir wood ranged from <0.001% to 0.005%. A significantly higher sulfur content was observed for live and dead branches. When comparing the relative relationship between TCDD classes and between tree parts, it is obvious that tree parts responsible for assimilation have significantly higher sulfur content than pulpwood and branches. Analysis of variance showed that spruce bark and side live branches have statistically significantly different sulfur content among TCDD classes (Table A16). The bark of dead spruce trees had statistically significantly higher (Table A17) sulfur content (0.11%) than the bark of severely defoliated spruce trees (0.065%) and healthy trees (0.059%).

3.3.4. Calorific Value

The calorific value is presented as the main result of this study and one of the most valuable outcomes, as it unifies the results on ash content and elemental composition. The net calorific value of each sampled tree part among TCDD classes is shown in Figure 6 for silver fir (a) and Norway spruce (b). Generally, silver fir had a higher net calorific value than Norway spruce. Previous studies reported a net calorific value in the range between 18.66 MJ/kg and 18.76 MJ/kg for spruce wood and between 18.84 MJ/kg and 19.29 MJ/kg for fir wood [75,95]. For both tree species, the wood of severely defoliated trees had a higher net calorific value than that of dead and healthy trees, but the difference was not statistically significant (Table A18). An increase in the net calorific value of spruce (6.43%) and fir (3.24%) wood during fungal decomposition was previously reported [75], supporting our results. Namely, the net calorific value of severely defoliated silver fir wood was only 0.18% and 0.12% higher than that of healthy and dead fir trees, respectively, while in the case of Norway spruce, the wood of severely defoliated trees had 0.07% and 0.46% higher net calorific values than the wood of dead and healthy trees, respectively. Further, for silver fir, the highest net calorific value was found for side live branches of healthy trees (20.47 MJ/kg), followed by side live branches of severely defoliated trees (20.45 MJ/kg), while in the case of Norway spruce, the highest net calorific value was found for side live branches of severely defoliated trees (20.05 MJ/kg) followed by side dead branches of severely defoliated spruce trees (19.75 MJ/kg). Main live branches of silver fir had a higher net calorific value than fir wood, while in the case of Norway spruce, main live branches showed a lower net calorific value than spruce wood, indicating another difference between species. The determined net calorific value of bark samples was in the expected range (17.5–20.5 MJ/kg) for coniferous virgin bark material given by HRN EN ISO 17225-1 [77]. Further, analysis of variance did not show any statistically significant difference in the net calorific value of bark material between TCDD classes (Table A18). Statistically significant differences were found only for Norway spruce side live branches (Table A18), where the side live branches of severely defoliated trees had a higher net calorific value than those of healthy trees (Table A19).

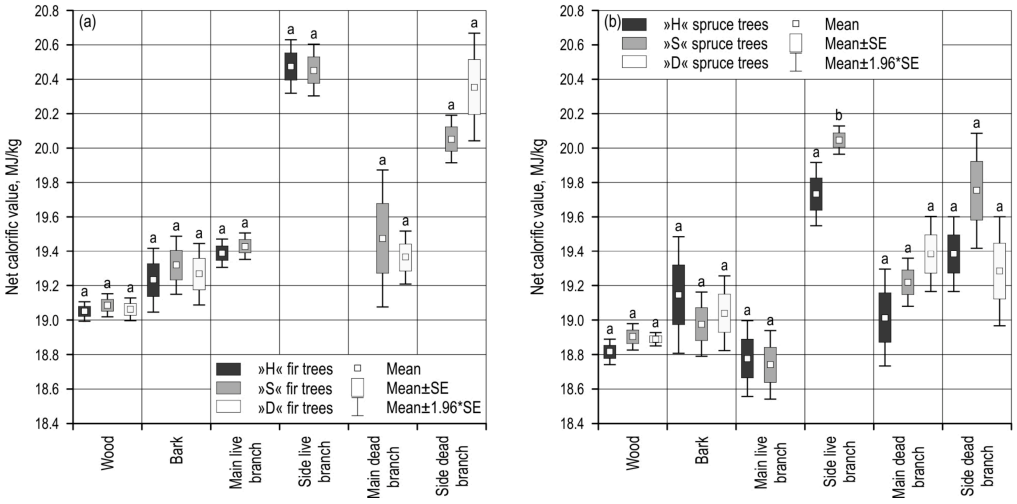

Figure 6. Net calorific values among tree parts and TCDD classes for (**a**) silver fir and (**b**) Norway spruce. (»H« healthy trees, »S« severely defoliated trees, »D« dead trees; different letters denote homogenous groups at the tree part level).

Regardless of TCDD class, the determined net calorific value was in the following order: wood < bark < main live branches < main dead branches < side dead branches < side live branches for silver fir and main live branches < wood < bark < main dead branches < side dead branches < side live branches for Norway spruce. A similar trend has been previously reported for coniferous species in China [96], supporting our findings.

4. Conclusions

This study was driven by accelerated climate change, which poses a significant challenge to the sustainability of forest ecosystems, sustainable forest management, and, consequently, renewable energy sources.

A study conducted on the tree parts, which are usually used as a solid biofuel, of Croatia's two most common coniferous species, silver fir and Norway spruce, provides insight into the amount and quality of branches, pulpwood bark and wood of by dieback-affected trees in the researched site. The results of this study indicate a significant reduction in branch biomass with increasing TCDD class for both tree species, underscoring the importance of continuously improving allometric equations used to calculate available biomass for energy, i.e., energy potential.

The results regarding the wood, bark, and branch biomass characteristics in terms of solid biofuel did not reveal a consistent difference between TCDD classes. For example, a statistically significant difference in net calorific value (one of the most important biofuel characteristics) was observed only for the side live branches of Norway spruce trees. On the other hand, although the side live and dead branches of both tree species had the highest net calorific value, these tree parts also contained almost twice the nitrogen content as recommended (0.60%), emphasising the complexity of biomass as a source of energy.

The overall results support including the degree of tree crown defoliation as an additional parameter in estimating the available branch biomass (quantity) that can be used as solid biofuel, but also the need for further research due to ambiguous results on the quality of individual components of the trees between TCDD classes.

Author Contributions: Conceptualization, B.U. and D.V.; methodology, B.U. and D.V.; validation, D.V. and B.U.; formal analysis, B.U. and D.V.; field measurements, B.U., M.L., I.Ž. and D.J.; laboratory analyses, B.U.; writing—original draft preparation, B.U. and D.V.; writing—review and editing, D.V. and B.U.; visualization, B.U.; supervision, D.V. project administration, A.Đ.; funding acquisition, A.Đ. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: Author David Janeš is employed by Forest Administration Office Delnice, Croatian Forests Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A. Materials and Methods

Table A1. Standards and laboratory equipment used in laboratory analyses.

Researched Feature	Used Standard	Used Equipment
Moisture content	HRN EN ISO 18134-2—Solid biofuels—Determination of moisture content—Part 2: Total moisture—Simplified method [61]	Heating chambers Binder FD 115 and Binder FD 250, Binder GmbH, Tuttlingen, Germany; Balance Kern 440-49A, KERN & SOHN GmbH, Balingen-Frommern, Germany
Sample preparation	HRN EN ISO 14780 Solid biofuels—Sample preparation [97]	Retsch SM 300 cutting mill; Mash size 0.5 mm, Retsch GmbH, Haan, Germany
Ash content	HRN EN ISO 18122—Solid biofuels—Determination of ash content [84]	Furnace Nabertherm P330, Nabertherm GmbH, Lilienthal, Germany; Analytical balance Mettler Toledo XA204, Mettler-Toledo AG, Greifensee, Switzerland
Moisture in general analysis sample	HRN EN ISO 18134-3:2015 Solid biofuels—Determination of moisture content—Oven-dry method—Part 3: Moisture in general analysis sample [98]	Heating chamber Binder FD 115, Binder GmbH, Tuttlingen, Germany; Analytical balance Mettler toledo XA204, Mettler-Toledo AG, Greifensee, Switzerland
Carbon, hydrogen, nitrogen, and sulfur content	HRN EN ISO 16948—Solid biofuels—Determination of total content of carbon, hydrogen, and nitrogen [99] HRN EN ISO 16994—Solid biofuels—Determination of total content of sulfur and chlorine [100]	Elementar Vario Macro Cube CHNS configuration, Elementar Analysensysteme GmbH, Langenselbold, Germany; Analytical balance Mettler toledo XA204. Mettler-Toledo AG, Greifensee, Switzerland; Reference material: wood chips of Scots pine (*Pinus sylvestris* L), Institut für Bioenergie GmbH, Vienna, Austria
Calorific value	HRN EN ISO 18125—Solid biofuels—Determination of calorific value [62]	Calorimeter IKA C1/10; Analytical balance Mettler toledo XA204; IKA pelletized benzoic acid, IKA-Werke GmbH & Co. KG, Staufen, Germany

Appendix B. Results

Table A2. Descriptive statistics of measured disc diameter, bark thickness and wood density.

Tree Species	Tree Crown Defoliation Degree		Healthy Trees	Severely Defoliated Trees	Dead Trees
Silver fir	Number of samples		27	25	25
	Disc diameter, cm	Average	22.93	23.18	25.45
		Sd. deviation	2.98	3.91	6.61
		Minimum	17.35	15.95	12.90
		Maximum	28.35	30.8	38.10
	Bark thickness, cm	Average	1.72	1.87	1.71
		Sd. deviation	0.45	0.56	0.56
		Minimum	1.10	0.80	1.15
		Maximum	2.90	3.05	2.75
	Nominal wood density, kg/m^3	Average	386.25	387.38	355.65
		Sd. deviation	34.60	31.07	41.85
		Minimum	303.90	334.5	226.10
		Maximum	452.10	471.8	403.50
Norway spruce	Number of samples		32	43	38
	Disc diameter, cm	Average	20.48	21.67	22.80
		Sd. deviation	3.47	4.48	6.94
		Minimum	15.27	11.41	7.52
		Maximum	31.82	30.55	34.80
	Bark thickness, cm	Average	1.30	1.54	1.18
		Sd. deviation	0.33	0.34	0.59
		Minimum	0.58	0.69	0.24
		Maximum	1.99	2.2	1.90
	Nominal wood density, kg/m^3	Average	408.33	417.51	385.49
		Sd. deviation	51.53	41.81	31.18
		Minimum	322.30	345.90	333.10
		Maximum	522.00	524.70	458.40

Table A3. Scheffe's post hoc test of significant differences in wood basic density between TCDD classes.

Tree Species	Silver Fir			Norway Spruce		
TCDD	»H«	»S«	»D«	»H«	»S«	»D«
»H«		0.9936	0.0123		0.6432	0.0788
»S«	0.9936		0.0106	0.6432		0.0036
»D«	0.0123	0.0106		0.0788	0.0036	

TCDD—tree crown defoliation degree; »H«—healthy trees; »S«—severely defoliated trees; »D«—dead trees.

Table A4. Regression equation of determined branch biomass among TCDD classes.

Tree Species	TCDD Class	Equation	Coefficient of Determination
Silver fir	Healthy tree	$BM_{OD} = 0.0447 \times DBH^{2.2672}$	0.4775
	Severely defoliated tree	$BM_{OD} = 0.0821 \times DBH^{2.0401}$	0.4112
	Dead tree	$BM_{OD} = 0.4811 \times DBH^{2} - 35.771 \times DBH + 709.84$	0.4599
Norway spruce	Healthy tree	$BM_{OD} = 0.2553 \times DBH^{1.8086}$	0.6119
	Severely defoliated tree	$BM_{OD} = 0.0901 \times DBH^{1.9982}$	0.6926
	Dead tree	$BM_{OD} = 0.0081 \times DBH^{2.4764}$	0.7231

BM_{OD}—oven-dry branch biomass.

Table A5. Analysis of variance of the TCDD classes' influence on the branch biomass among DBH classes.

Tree Species	DBH	N	SS Effect	Df Effect	MS Effect	SS Error	Df Error	MS Error	F	*p*
Silver fir	37.5	13	53,647.32	2	26,823.66	27,599.39	10	2759.94	9.72	0.0045
	42.5	19	67,703.66	2	33,851.83	85,834.43	16	5364.65	6.31	0.0095
	47.5	19	140,657.2	2	70,328.60	186,106.7	16	11,631.67	6.05	0.0111
	52.5	20	168,829.2	2	84,414.61	106,517.7	17	6265.75	13.47	0.0003
	57.5	10	169,398.4	2	84,699.18	35,525.15	7	5075.02	16.69	0.0022
Norway spruce	37.5	16	50,380.45	2	25,190.22	11,892.87	13	914.84	27.54	<0.0001
	42.5	19	91,873.68	2	45,936.84	87,992.93	16	5499.56	8.35	0.0033
	47.5	14	5706.827	2	2853.41	47,931.33	11	4357.39	0.65	0.5386
	52.5	18	111,406.0	2	55,703.02	101,522.0	15	6768.13	8.23	0.0039
	57.5	19	124,836.8	2	62,418.39	84,696.24	16	5293.52	11.79	0.0007

DBH—diameter at breast height, N—number of trees.

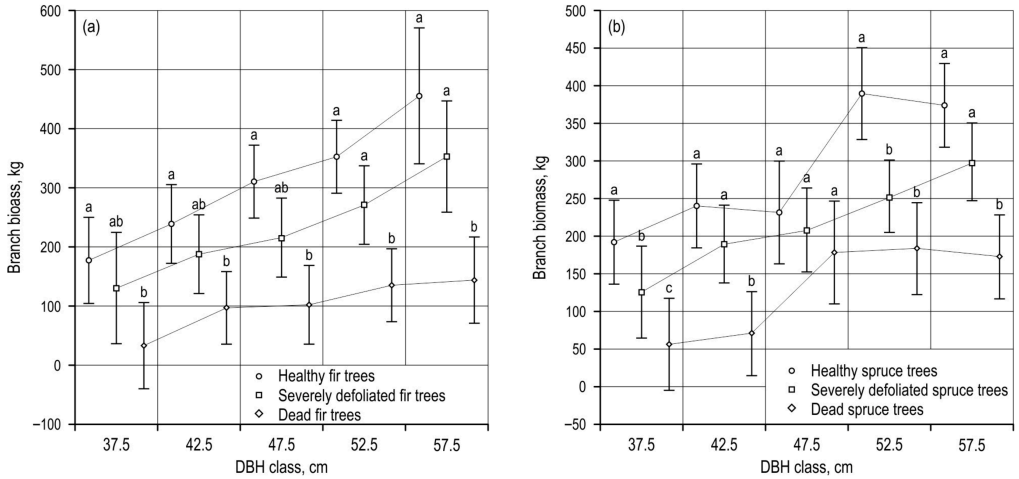

Figure A1. Average branch biomass among DBH and TCDD classes for (**a**) silver fir and (**b**) Norway spruce (vertical bars denote 0.95 confidence intervals; different letters denote homogenous groups at DBH class level).

Table A6. Scheffe's post hoc test of significant differences in branch biomass between TCDD classes among DBH classes.

		Silver Fir			Norway Spruce		
DBH Class	**TCDD**	**»H«**	**»S«**	**»D«**	**»H«**	**»S«**	**»D«**
37.5	»H«		0.499448	0.004962		0.010760	0.000021
	»S«	0.499448		0.082420	0.010760		0.010499
	»D«	0.004962	0.082420		0.000021	0.010499	
42.5	»H«		0.495423	0.010940		0.485550	0.004146
	»S«	0.495423		0.115509	0.485550		0.034706
	»D«	0.010940	0.115509		0.004146	0.034706	
47.5	»H«		0.311906	0.011074		0.862471	0.540693
	»S«	0.311906		0.220385	0.862471		0.785852
	»D«	0.011074	0.220385		0.540693	0.785852	
52.5	»H«		0.211445	0.000344		0.034788	0.004612
	»S«	0.211445		0.022459	0.034788		0.355496
	»D«	0.000344	0.022459		0.004612	0.355496	
57.5	»H«		0.344645	0.003802		0.210787	0.000798
	»S«	0.344645		0.015103	0.210787		0.022069
	»D«	0.003802	0.015103		0.000798	0.022069	

DBH—diameter at breast height; TCDD—tree crown defoliation degree; »H«—healthy trees; »S«—severely defoliated trees; »D«—dead trees.

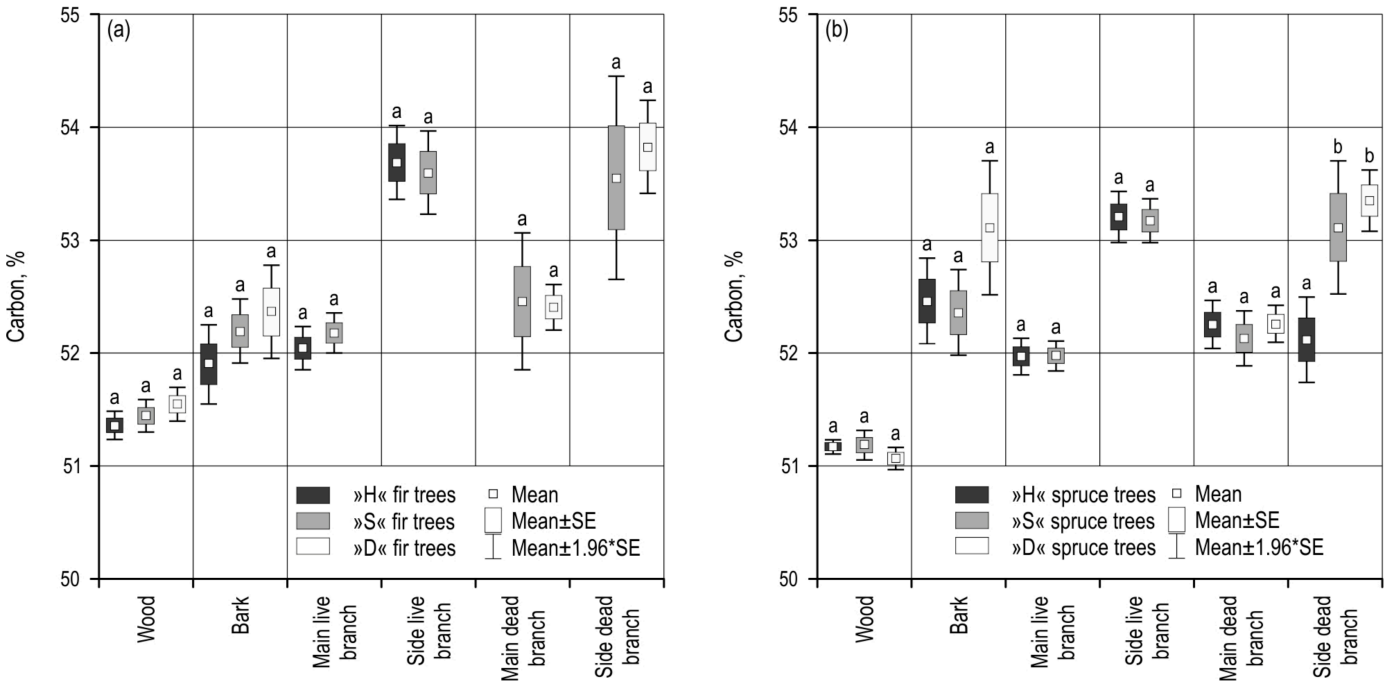

Figure A2. Carbon content among tree parts and TCDD classes for (**a**) silver fir and (**b**) Norway spruce. (»H« healthy trees, »S« severely defoliated trees, »D« dead trees; different letters denote homogenous groups at tree part level).

Table A7. Number of tested samples among TCDD class and tree species.

Tree Species	TCDD	Moisture Content	Ash Content	CHNS Content	Calorific Value
Silver fir	Healthy trees	108	108	108	108
	Severely defoliated trees	107	107	107	107
	Dead trees	106	106	106	106
	Total	321	321	321	321
Norway spruce	Healthy trees	152	152	152	152
	Severely defoliated trees	201	201	201	201
	Dead trees	139	139	139	139
	Total	492	492	492	492
	Total	813	813	813	813

Table A8. Descriptive statistics of determined ash content.

Tree Species	TCDD	Tree Part	Number of Samples	Average	Standard Deviation	Minimum	Maximum
Silver fir	»H«	Wood	27	0.43	0.14	0.3	0.9
	»S«		25	0.50	0.18	0.3	1
	»D«		30	0.56	0.24	0.3	1.7
	»H«	Main live branches	27	2.45	0.49	1.8	3.6
	»S«		25	2.43	0.56	1.7	3.5
	»H«	Side live branches	27	5.44	0.91	3.9	7.8
	»S«		25	5.46	1.00	3.7	7.2
	»S«	Main dead branches	4	2.48	0.53	2	3.2
	»D«		30	2.55	0.73	0.5	3.9
	»S«	Side dead branches	3	3.87	0.58	3.2	4.2
	»D«		18	4.23	0.51	3.6	5.2
	»H«	Bark	27	3.67	0.72	2.5	6.1
	»S«		25	3.74	0.69	2.5	4.8
	»D«		28	4.35	0.98	2.7	6.6
Norway spruce	»H«	Wood	32	0.35	0.07	0.3	0.6
	»S«		43	0.40	0.15	0.3	1.2
	»D«		38	0.37	0.06	0.3	0.5
	»H«	Main live branches	33	2.09	0.51	1.2	3.3
	»S«		43	2.43	0.45	1.2	3.3
	»H«	Side live branches	33	4.46	0.62	3.2	5.8
	»S«		43	4.50	0.70	3.3	5.9
	»H«	Main dead branches	15	1.87	0.71	0.7	3
	»S«		19	2.36	1.16	0.6	4.5
	»D«		38	1.87	0.73	0.6	3.4
	»H«	Side dead branches	7	3.29	0.70	2.5	4.7
	»S«		10	3.33	1.10	1.5	4.6
	»D«		27	3.85	0.63	2.6	5.8
	»H«	Bark	33	3.47	0.63	2	4.7
	»S«		42	4.02	1.19	2.6	8.6
	»D«		36	4.94	1.41	2.8	8.4

TCDD—tree crown defoliation degree; »H«—healthy trees; »S«—severely defoliated trees; »D«—dead trees.

Table A9. Scheffe's post hoc test of significant differences in ash content between TCDD classes.

Tree Species	Tree Part	TCDD		
	Bark	**»H«**	**»S«**	**»D«**
Silver fir	»H«		0.953367	0.011143
	»S«	0.953367		0.029545
	»D«	0.011143	0.029545	
Norway spruce	Main live branches	»H«	»S«	
	»H«		0.002859	
	»S«	0.002859		
	Bark	»H«	»S«	»D«
	»H«		0.122886	0.000003
	»S«	0.122886		0.002480
	»D«	0.000003	0.002480	

TCDD—tree crown defoliation degree; »H«—healthy trees; »S«—severely defoliated trees; »D«—dead trees.

Table A10. Analysis of variance in the carbon content between TCDD classes among all tree parts.

Tree Species	Tree Part	SS Effect	Df Effect	MS Effect	SS Error	Df Error	MS Error	F	*p*
Silver fir	Wood	0.4989	2.	0.2495	11.1604	79	0.1413	1.7659	0.1777
	Bark	3.0403	2	1.5202	69.1946	77	0.8986	1.6917	0.1910
	Main live branches	0.2393	1	0.2393	11.7457	50	0.2349	1.0186	0.3177
	Side live branches	0.1045	1	0.1045	40.6313	50	0.8126	0.1285	0.7215
	Main dead branches	0.0091	1	0.0091	10.3205	32	0.3225	0.0282	0.8677
	Side dead branches	0.1925	1	0.1925	14.7517	19	0.7764	0.2479	0.6242
Norway spruce	Wood	0.3200	2	0.1600	12.5681	110	0.1143	1.4006	0.2508
	Bark	12.3323	2	6.1664	222.1506	109	2.0381	3.0256	0.0526
	Main live branches	0.0005	1	0.0005	15.7861	74	0.2133	0.0024	0.9610
	Side live branches	0.0202	1	0.0202	31.6313	74	0.4275	0.0472	0.8286
	Main dead branches	0.2424	2	0.1212	17.5855	69	0.2549	0.4755	0.6236
	Side dead branches	8.4150	2	4.2075	23.0263	41	0.5616	7.4918	0.0017

Table A11. Scheffe's post-hoc test of significant differences in carbon share between TCDD classes for Norway spruce side dead branches.

TCDD	»H«	»S«	»D«
»H«		0.035649	0.001688
»S«	0.035649		0.697698
»D«	0.001688	0.697698	

TCDD—tree crown defoliation degree; »H«—healthy trees; »S«—severely defoliated trees; »D«—dead trees.

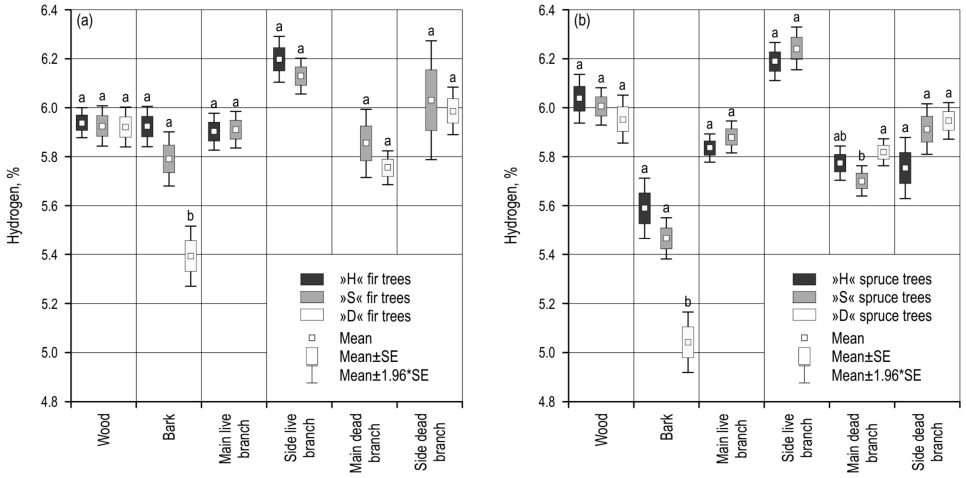

Figure A3. Hydrogen content among tree parts and TCDD classes for (**a**) silver fir and (**b**) Norway spruce. (»H« healthy trees, »S« severely defoliated trees, »D« dead trees; different letter denotes homogenous group at tree part level).

Table A12. Analysis of variance in the hydrogen content between TCDD classes among all tree parts.

Tree Species	Tree Part	SS Effect	Df Effect	MS Effect	SS Error	Df Error	MS Error	F	*p*
Silver fir	Wood	0.0047	2	0.0024	3.2438	79	0.0411	0.0578	0.9439
	Bark	4.1824	2	2.0912	6.1273	77	0.0796	26.2796	<0.0001
	Main live branches	0.0009	1	0.0009	1.9116	50	0.0382	0.0245	0.8761
	Side live branches	0.0615	1	0.0615	2.4293	50	0.0486	1.2659	0.2659
	Main dead branches	0.0349	1	0.0349	1.1382	32	0.0356	0.9802	0.3296
	Side dead branches	0.0049	1	0.0049	0.8430	19	0.0444	0.1097	0.7441
Norway spruce	Wood	0.1246	2	0.0623	8.7602	110	0.0796	0.7820	0.4600
	Bark	5.8260	2	2.9130	12.6024	109	0.1156	25.1952	<0.0001
	Main live branches	0.0384	1	0.0384	2.9132	74	0.0394	0.9763	0.3263
	Side live branches	0.0537	1	0.0537	5.2361	74	0.0708	0.7596	0.3863
	Main dead branches	0.1733	2	0.0867	1.7109	69	0.0248	3.4950	0.0358
	Side dead branches	0.2056	2	0.1028	1.4343	41	0.0350	2.9384	0.0642

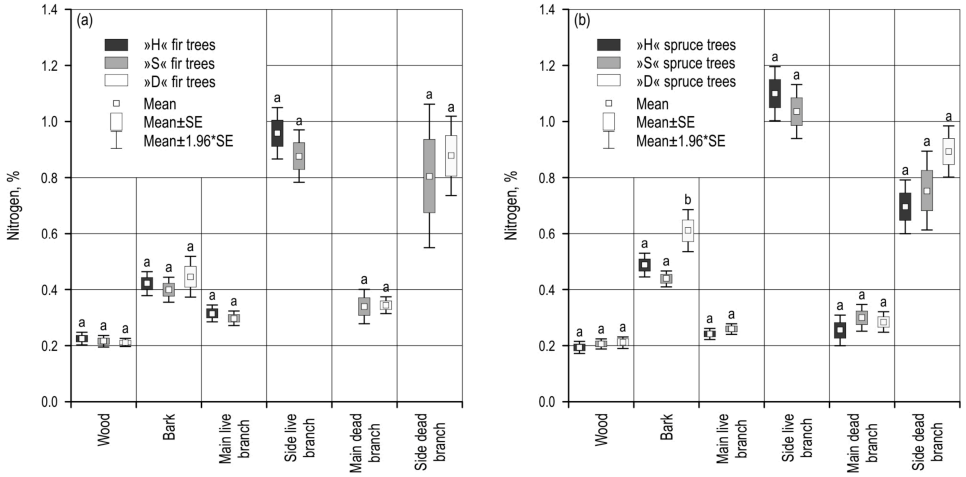

Figure A4. Nitrogen content among tree parts and TCDD classes for (**a**) silver fir and (**b**) Norway spruce. (»H« healthy trees, »S« severely defoliated trees, »D« dead trees; different letter denotes homogenous group at tree part level).

Table A13. Scheffe's post hoc test of significant differences in hydrogen share between TCDD classes.

Tree Species	Tree Part	TCDD		
	Bark	**»H«**	**»S«**	**»D«**
Silver fir	»H«		0.247649	0.000000
	»S«	0.247649		0.000012
	»D«	0.000000	0.000012	
Norway spruce	Main dead branches	»H«	»S«	»D«
	»H«		0.416114	0.654141
	»S«	0.416114		0.036054
	»D«	0.654141	0.036054	
	Bark	»H«	»S«	»D«
	»H«		0.299283	0.000000
	»S«	0.299283		0.000002
	»D«	0.000000	0.000002	

TCDD—tree crown defoliation degree; »H«—healthy trees; »S«—severely defoliated trees; »D«—dead trees.

Table A14. Analysis of variance in the nitrogen content between TCDD classes among all tree parts.

Tree Species	Tree Part	SS Effect	Df Effect	MS Effect	SS Error	Df Error	MS Error	F	*p*
Silver fir	Wood	0.0028	2	0.0014	0.2074	79	0.0026	0.5286	0.5915
	Bark	0.0285	2	0.0142	1.6888	77	0.0219	0.6490	0.5254
	Main live branches	0.0039	1	0.0039	0.2706	50	0.0054	0.7259	0.3983
	Side live branches	0.0861	1	0.0861	2.9117	50	0.0582	1.4791	0.2296
	Main dead branches	0.0001	1	0.0001	0.2142	32	0.0067	0.0127	0.9111
	Side dead branches	0.0134	1	0.0134	1.7007	19	0.0895	0.1496	0.7032
Norway spruce	Wood	0.0052	2	0.0026	0.4248	110	0.0039	0.6681	0.5148
	Bark	0.6013	2	0.3006	2.7464	109	0.0252	11.9319	<0.0001
	Main live branches	0.0056	1	0.0056	0.2757	74	0.0037	1.5097	0.2231
	Side live branches	0.0762	1	0.0762	6.9187	74	0.0935	0.8146	0.3697
	Main dead branches	0.0173	2	0.0086	0.8526	69	0.0124	0.6985	0.5008
	Side dead branches	0.2912	2	0.1456	2.0860	41	0.0509	2.8617	0.0686

Table A15. Scheffe's post-hoc test of significant differences in nitrogen share between TCDD classes for Norway spruce bark.

TCDD	»H«	»S«	»D«
»H«		0.415250	0.007012
»S«	0.415250		0.000029
»D«	0.007012	0.000029	

TCDD—tree crown defoliation degree; »H«—healthy trees; »S«—severely defoliated trees; »D«—dead trees.

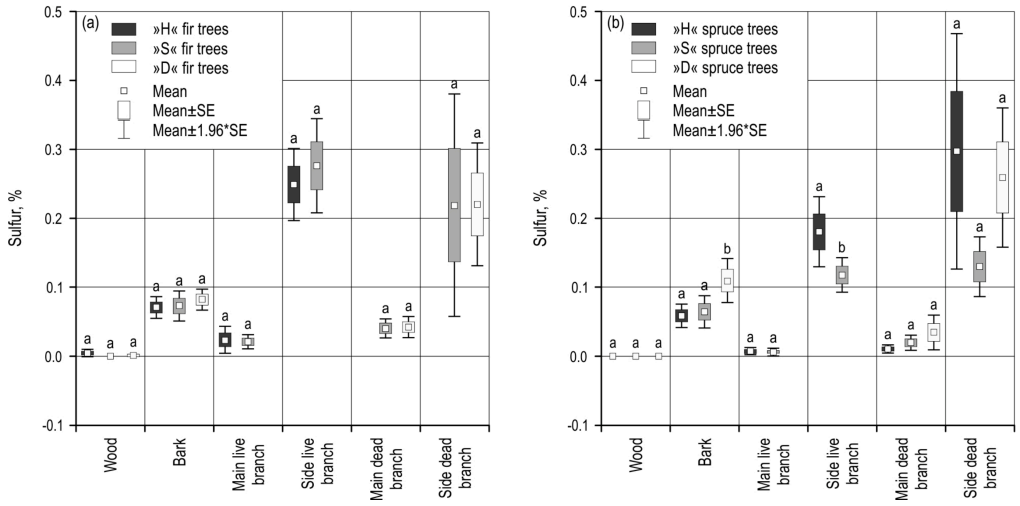

Figure A5. Sulfur content among tree parts and TCDD classes for (**a**) silver fir and (**b**) Norway spruce. (»H« healthy trees, »S« severely defoliated trees, »D« dead trees; different letter denotes homogenous group at tree part level).

Table A16. Analysis of variance in the sulfur content between TCDD classes among all tree parts.

Tree Species	Tree Part	SS Effect	Df Effect	MS Effect	SS Error	Df Error	MS Error	F	*p*
Silver fir	Wood	0.0003	2	0.0002	0.0064	79	0.0001	1.8939	0.1573
	Bark	0.0020	2	0.0010	0.1640	77	0.0021	0.4707	0.6264
	Main live branches	0.0001	1	0.0001	0.0855	50	0.0017	0.0553	0.8150
	Side live branches	0.0096	1	0.0096	1.2278	50	0.0246	0.3929	0.5336
	Main dead branches	0.0000	1	0.0000	0.0533	32	0.0017	0.0062	0.9378
	Side dead branches	0.0000	1	0.0000	0.6754	19	0.0355	0.0001	0.9927
Norway spruce	Wood	0.0000	2	0.0000	0.0000	110	0.0000	0.9866	0.3761
	Bark	0.0563	2	0.0281	0.6654	109	0.0061	4.6092	0.0120
	Main live branches	0.0000	1	0.0000	0.0105	74	0.0001	0.0339	0.8545
	Side live branches	0.0740	1	0.0740	1.0117	74	0.0137	5.4128	0.0227
	Main dead branches	0.0071	2	0.0035	0.2434	69	0.0035	1.0011	0.3728
	Side dead branches	0.1533	2	0.0766	2.2242	41	0.0542	1.4129	0.2551

Table A17. Scheffe's post hoc test of significant differences in sulfur content between TCDD classes for Norway spruce.

	TCDD	»H«	»S«	»D«
Side live branches	»H«		0.022731	
	»S«	0.022731		
Bark	»H«		0.950635	0.028778
	»S«	0.950635		0.041229
	»D«	0.028778	0.041229	

TCDD—tree crown defoliation degree; »H«—healthy trees; »S«—severely defoliated trees; »D«—dead trees.

Table A18. Analysis of variance in the net calorific value between TCDD classes among all tree parts.

Tree Species	Tree Part	SS Effect	Df Effect	MS Effect	SS Error	Df Error	MS Error	F	*p*
Silver fir	Wood	0.0167	2	0.0083	2.2899	79	0.0290	0.2878	0.7507
	Bark	0.2349	1	0.2349	7.8265	19	0.4119	0.5702	0.4594
	Main live branches	0.0215	1	0.0215	2.2054	50	0.0441	0.4878	0.4882
	Side live branches	0.0056	1	0.0056	7.9383	50	0.1588	0.0354	0.8515
	Main dead branches	0.0437	1	0.0437	5.9080	32	0.1846	0.2370	0.6297
	Side dead branches	0.2349	1	0.2349	7.8265	19	0.4119	0.5702	0.4594
Norway spruce	Wood	0.2349	1	0.2349	7.8265	19	0.4119	0.5702	0.4594
	Bark	0.5410	2	0.2705	63.1877	109	0.5797	0.4666	0.6284
	Main live branches	0.0249	1	0.0249	31.7878	74	0.4296	0.0580	0.8104
	Side live branches	1.8389	1	1.8389	12.4573	74	0.1683	10.9239	0.0015
	Main dead branches	0.5519	2	0.2759	14.8128	69	0.2147	1.2854	0.2831
	Side dead branches	1.5978	2	0.7989	21.6031	41	0.5269	1.5162	0.2316

Table A19. Scheffe's post hoc test of significant differences in calorific value between TCDD classes for Norway spruce side live branches.

TCDD	»H«	»S«
»H«		0.001466
»S«	0.001466	

TCDD—tree crown defoliation degree; »H«—healthy trees; »S«—severely defoliated trees.

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