forests

MDPI

Article

How the Spruce Ageing Process Affects Wood

Tomasz Jelonek, Katarzyna Klimek, Bartłomiej Naskrent *, Arkadiusz Tomczak, Witold Grzywiński, Joanna Kopaczyk, Tomasz Szwed, Daniel Grabowski and Jarosław Szaban

Department of Forest Utilization, Faculty of Forestry and Wood Technology, Poznan University of Life Sciences, Wojska Polskiego 71A, 60-625 Poznan, Poland; tomasz.jelonek@up.poznan.pl (T.J.)

* Correspondence: bartlomiej.naskrent@up.poznan.pl

Abstract: Climate change and the gradual phaseout of the spruce from Central Europe inspired us to study the effects of the ageing process of trees on wood properties. This study was conducted in old tree stands with significant involvement of the spruce (*Picea abies* (L.) H. Karst) in the ages between 122 and 177 years. The study material (samples) was collected from the selected trees to study wood properties such as density, resilience to compressive strength, resilience to bending strength, and modulus of elasticity. The results and findings of this study indicate that the spruce currently reaches the optimal technical quality of wood tissue at approximately 60 years of age. It is approximately 20 years earlier than the planned cutting age for the species. This could be due to water stress which led to adaptive changes in the wood tissue and earlier technical maturation of the wood in the studied trees. Significant radiant variabilities of wood properties of the Norway spruce were observed. It was determined that wood density does not fully reflect its mechanical properties, and it can be considered an indicator of the technical quality of wood tissue, but only within a limited scope. The results obtained may not only be applied in optimising the use of wood from spruce stands. They can also indicate the need to change the approach to managing spruce stands and their conversion towards broadleaf species.

Keywords: spruce; wood properties; tree ageing process; cavitation; climate change

check for updates

Citation: Jelonek, T.; Klimek, K.; Naskrent, B.; Tomczak, A.; Grzywiński, W.; Kopaczyk, J.; Szwed, T.; Grabowski, D.; Szaban, J. How the Spruce Ageing Process Affects Wood. *Forests* **2024**, *15*, 1737. https://doi.org/10.3390/f15101737

Academic Editor: Boštjan Lesar

Received: 20 August 2024
Revised: 19 September 2024
Accepted: 25 September 2024
Published: 30 September 2024

1. Introduction

Wood is a chemically complex material. It denotes the characteristic anatomical construction of a particular tree species, which affects its mechanical and physical properties. Differences in the structure and properties of wood can even occur within a single species, e.g., depending on the geographical location [1,2]. Moreover, the features and properties of wood tissue can differ in a single tree depending on its age, the ratio of young wood to old wood, the ratio of early wood to late wood in the annual rings, the ratio of hardwood to sapwood, and individual wood defects [3]. Hence, it is particularly significant to obtain raw material at the optimal cutting age for a given species.

Leaving overmature tree stands may expose them to diseases which cause depreciation of the wood on the stem and decrease the biological and mechanical stability of the entire tree stand. According to Bernadzki [4], in older overmature tree stands, the greatest threat to the tree tissue is the decay (rot), and the share of rot-affected trees increases with the age of the tree stand.

Climate change is currently a significant threat to ecosystems, particularly forest ecosystems [5–7]. Preserving the stability of tree stands is crucial for maintaining the continuous formation of wood and mitigating climate change through carbon sequestration and preservation of forest ecosystems [7,8]. According to Borecki et al. [9], climate change significantly impacts the health of tree stands in older age groups. Climate models based on simulations predict that European forests will be exposed to more frequent and longer droughts and higher air temperatures [10]. Persistent droughts cause water stress and contribute to weakening spruce tree stands by increasing their vulnerability to pests and pathogens [11], e.g., the European spruce bark beetle (*Ips typographus*), one of the most aggressive and fast-spreading bark beetles [12]. According to Jyske et al. [13], the spruce returns to a state of physiological balance once drought recedes, as long as it is not long-lasting. However, an increasing number of extended periods of drought have been documented. As a result of these threats, there can be a shift of the natural habitats of the tree species that are important for the economy and the self-thinning processes intensify [14–16]. In addition to climate change, spruce tree stands are weakened by a mixture of pollutants, mainly nitric oxide, sulphur oxide, and heavy metals [17]. Sulphur dioxide is produced mainly by coal-fired power stations and the chemical industry, which has caused a significant decay of many hectares of spruce forest [18]. As a result of the mass dieback of spruce tree stands in Europe, a number of scientists have started conducting research into the phenomenon, among them Svoboda et al. [19], Brůna et al. [20], Kharuk et al. [11], and Toth et al. [12]. The spruce prefers moist habitants and is not able to adapt to climate change and drought within a short period of time; according to some prognoses, the spruce will be ousted by species that are more resilient to high temperatures in specific habitats. Pötzelsberger et al. [21] and Zaidler et al. [7] state that the Norway spruce can be substituted by introducing species from regions with similar climatic conditions. The inclusion of species with adequate productive potential can improve the adaptability of tree stands [22]. Other non-native spruce species can constitute alternatives to the native Norway spruce [6]. Certainly in the near future, forestry and also forest sciences will face further challenges to understand and prepare for the inevitable changes in forest ecosystems.

Environmental changes, including climate and anthropogenic changes, as well as stress factors can affect the physical and mechanical properties of wood. According to Wimmer and Grabner [23], the ratio of late wood increases with the amount of precipitation during summer months. Above-average precipitation can cause premature stoppage of early wood formation, thereby extending the time of late wood formation. The increased amount of precipitation has an indirect effect on wood density.

Current methods of tree management, including removal, cultivation, and assessment of mechanical resilience, are predominantly based on visual assessment and personal experience of forest rangers [24]. One of the key factors, apart from the external forces, tree morphology, or features of the tree stands, is the value of the mechanical resilience of the tree tissue. Spruce wood is an excellent building material which possesses a high load-bearing capacity, particularly in terms of bending [7,25]. There is a strong and negative correlation between the angle of the microfibrils and the modulus of elasticity in the spruce [24,26,27]. Moore [28] determined the mean values for modulus of rupture and modulus of elasticity for the Sitka spruce with a moisture content of 12% at approximately 60 Nmm^{-2} and 8000 Nmm^{-2}. According to Jelonek et al. [29], the value of modulus of elasticity for 95-year-old healthy spruce wood is 10.679 Nmm^{-2}. Slightly higher values were obtained by Verkazalo and Leban [30], who conducted research in France and Finland, and they were 10,035 Nmm^{-2} and 12,872 Nmm^{-2} for modulus of elasticity (MOE), respectively, and 58.9 Nmm^{-2} and 82.3 Nmm^{-2} for modulus of rupture (MOR). Similar results were obtained by Bacher and Krzosek [31], who conducted a study in Poland. However, Mclean [32] stated that in the case of defect-free spruce wood, the mean modulus of rupture is between 59 Nmm^{-2} and 67 Nmm^{-2}; however, in damaged wood, it can drop to 30 Nmm^{-2}, whereas in the case of healthy spruce wood, the mean value of modulus of elasticity is 6800 Nmm^{-2}. Modulus of elasticity, similarly to modulus of rupture, statistically depends on the number of features of the wood tissue, as well as defects and anomalies.

This study assumes that the age of the trees will significantly determine the physical and mechanical properties of the formulated wood. Trees, similar to any other organism, will be subjected to an ageing process; wood tissue formulated in tree stands above the cutting age will exhibit significantly different properties from the wood tissue formed at a young age.

The main aim of this study was to determine the impact of the spruce ageing process on the variability of selected physical and mechanical wood properties. Based on the variability, an approximate age was determined, which exhibited the optimal technical quality of wood tissue. The aim of this study was to determine the relationship between the studied properties. Owing to the mass dieback of the spruce in Europe, the subject of research seems particularly important. In the next few years, it will not be possible to study such old spruce because it will no longer grow in Central Europe, particularly in the lowlands.

2. Materials and Methods

This study was conducted in 2020–2022 in Poland at three locations in five research areas (plots) (Figure 1). Mature (overmature) tree stands with spruces between 122 and 177 years of age were selected for the study (Table 1).

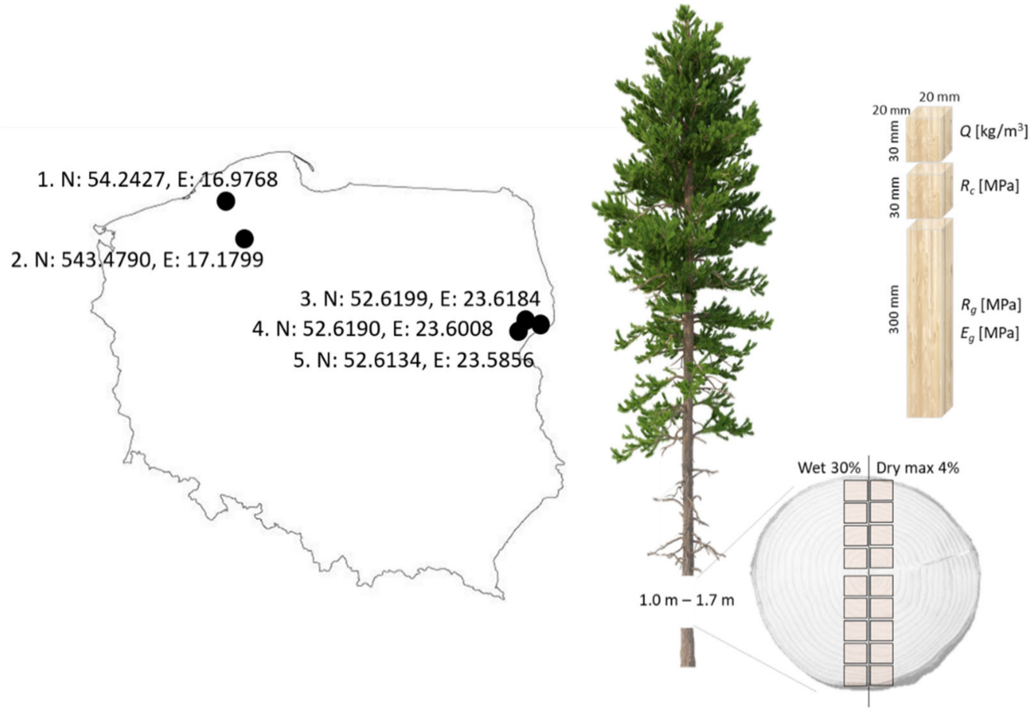

Figure 1. Localisation of research areas and diagram of collecting samples from model trees.

Table 1. Basic location and tree characteristics.

Plot	Tree Number	Height [m]	DBH [cm]	Average Age of Sample Trees	Stand Quality Class	GPS (WGS-84)
1/Warcino Forest District	1 2 3	31.3 30.2 29.2	43.0 41.5 39.5	124	I	N: 54.2427, E: 16.9768
2/Lipka Forest District	1 2 3	29.4 28.5 27.5	46.5 44.0 42.5	122	II	N: 543.4790, E: 17.1799
3/Bialowieza Forest	1 2 3	36.9 36.0 34.8	64.5 63.0 60.0	177	I	N: 52.6199, E: 23.6184
4/Bialowieza Forest	1 2 3	32.2 30.9 29.8	50.5 48.0 47.5	123	II	N: 52.6190, E: 23.6008
5/Bialowieza Forest	1 2 3	33.8 33.2 32.5	62.5 60.0 58.0	175	II	N: 52.6134, E: 23.5856

Model trees were selected by simultaneously applying environmental and dendrometric methods. For this purpose, a research plot was established in each tree stand to measure the diameter at breast height (DBH) of all the trees and classify them following Kraft's classes [33]. Next, the main tree stand (I, II, and III Kraft's class) was divided into three degrees of thickness following the dendrological method [34]. Based on the thickness and width properties, an average tree from each class was selected, that is, three model trees were selected from each area. A total of fifteen model trees were cut from five research plots.

A sample, i.e., a 70 cm block, was collected from each model tree; each sample was collected at a height between 1.0 m and 1.7 m (Figure 1). The material for laboratory testing was collected in the form of matching blocks, which were then cut to size in order to determine the mechanical properties and wood density of wet wood in a state of maximal saturation of the fibres (30% moisture content) and dry wood (maximum 4% moisture content). Material was collected to determine the variation in wood density, compressive strength, static bending strength, and static bending modulus of elasticity.

2.1. Wood Properties of Spruce Wood

This study determined the radial variability of compressive strength (*Rc*), bending strength (*Rg*), and modulus of elasticity of wood (*E*) in two extreme states of moisture content, that is, dry wood with max. 4% saturation and wet wood (wood above the saturation point of cell membranes, i.e., above 30%). Moreover, the conventional density of wood was also determined (q). The mechanical wood properties were studied using a universal testing machine TiraTESt with the MatestService software 2013.

2.2. Wood Density of Spruce Wood

The conventional density was determined using a stereometric method following the guidelines collected in ISO 13061-2:2014 standards [35].

Basic density was calculated using the following formula:

$$q = \frac{m_0}{V_{max}} \quad [\frac{\mathrm{kg}}{\mathrm{m}^3}] \tag{1}$$

where: q—basic density;

m_0—mass of dry wood [kg];

V_{max}—the volume of wet wood in the state of maximum moisture content [m^3].

2.3. Compressive Strength of Spruce Wood

The samples used to determine bending strength (*Rc*) were shaped as blocks with dimensions of 20 mm (a) × 20 mm (b) × 30 mm (h). They were dried using the drying and weighing method until they reached a maximum saturation of 4%. The external dimensions were measured using an electronic calliper, AOS ABSOLUTE Digimatic Standard (Mitutoyo America, Aurora, IL, USA), with an accuracy of ±0.1 mm.

In the next step, the samples were placed in a container with distilled water in order to obtain maximal moisture content (the moment at which the mass increment was not observed), and then, they were measured once more with a calliper and weighed with identical precision to the dry samples. Next, the samples were destroyed to obtain the maximal (destructive) value of compressive strength of the sample P_{max}, which was used to determine the resilience of wood to compressive strength along the grain R_c.

$$R_c = \frac{P_{max}}{A} [\mathrm{MPa}] \tag{2}$$

where: P_{max}—maximal (destructive) compressive strength on the sample [N];

A—cross-sectional area of the sample [mm^2].

Resilience analysis of compressive strength was conducted in accordance with the ISO 13061-17:2017 [36] standards with an accuracy of 0.01 [MPa].

2.4. Bending Strength of Spruce Wood

The samples were prepared according to ISO 3129:2019 [37] standards. The samples for static bending (R_g) were prepared in the shape of blocks with dimensions of 20 mm (a) × 20 mm (b) × 300 mm (h). The analysis was conducted on dry and wet samples, similar to the analysis of compressive strength (R_c). The external dimensions were measured using an electronic calliper, AOS ABSOLUTE Digimatic Standard, with an accuracy of ±0.1 mm. Next, the maximum value of the destructive strength was determined, which allowed the bending strength resilience to be calculated using the following formula:

$$R_g = \frac{3 \times P_{max} \times l}{2 \times b \times h^2} \text{ [MPa]} \quad (3)$$

where: P_{max}—destructive strength (bending) [N];
l—support spacing [mm];
b—width of the sample [mm];
h—height of the sample [mm].

2.5. Modulus of Elasticity of Wood in Bending

The modulus of elasticity in bending (E), resilience to bending, and destructive bending strength were determined in accordance with PN-EN 380:1998 standard [38]. The analysis of damages after the bending test was conducted on the basis of ASTM D 143–94: 2000 standard [39].

$$E = \frac{(P_i - P_1) \times l^3}{4(f_i - f_1) \times b \times h^3} \text{ [MPa]} \quad (4)$$

where: E—modulus of elasticity;
P_i—load of a given range [N];
P_1—preload [N];
l—support spacing [mm];
b—width of the sample [mm];
h—height of the sample [mm];
f_i—deflection value of the load of a given range [mm];
f_1—deflection value forced by preload.

2.6. Statistical Analyses

Over 2000 samples were used for statistical analyses. In the early stages of the mathematical and statistical analyses, the focus was on determining the characteristics of comparable groups of variables and choosing suitable tests. First, the distribution of populations following the Shapiro–Wilk test was used to verify whether there were differences between the populations. In populations with a distribution close to the normal distribution, a parametric HSD test was used, and in the case of non-normal distribution, a non-parametric test (the Kruskal–Wallis test) was used. The following terms were used to describe the distributions of the studied features: mean, median, decile range, standard deviation, and coefficient of variation. The correlation coefficient was calculated to determine the relationships between the variables. All statistical analyses were conducted with a statistical significance of $p < 0.05$ and a confidence interval of 95%. Statistical analyses were conducted using the STATISTICAS 14 set.

3. Results

The radial distribution of variables of the studied features and properties of spruce wood were analysed for this study on all research plots in all locations. The main aim of the experiment was to observe the trends of changing wood properties owing to the ageing processes of trees. The distribution of the studied properties was not always normal, and the variability of the studied properties was comparable within the research plot and the variability of the entire set of data, which significantly affected the distribution of the studied variables.

3.1. Wood Density of Spruce Wood

Wood density did not indicate a normal distribution, and its median was 354.78 kg/m^3.

The variability of this particular wood property was 11.4%, and the confidence interval at 95% indicated that the mean spruce wood density was in the range of 354 kg/m^3 to 367 kg/m^3 (Table 2).

Table 2. Statistical characteristics of conventional density of spruce wood.

q [kg/m^3]								
Mean	**Confidence −95%**	**Confidence +95%**	**Stand Dev.**	**Minimum**	**Maximum**	**Q 25**	**Median**	**Q 75**
360.29	353.76	366.81	44.24	277.11	522.93	331.86	354.78	377.51

Because the distribution of spruce wood density is not a normal distribution, it was also described using the median, which was slightly lower than the mean for every research plot.

The key element in the analysis of the impact of tree age on wood properties is the analysis of the radial variability of the studied features or properties; thus, the focus is on describing the variable density of the wood along the radius. The dotted horizontal line in Figure 2 marks the median for wood density, whereas the dotted vertical line is an approximate cutting age limit (+/−5 years) for the spruce, i.e., 80 years.

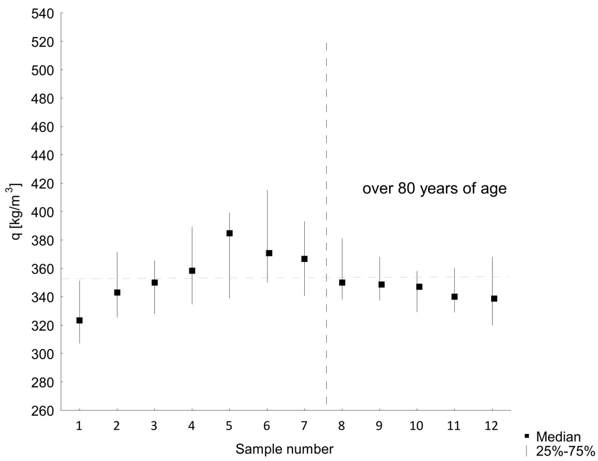

Figure 2. Radial variability of wood density.

The density medians increased gradually until the age of 60–65, and after which there was a gradual decrease in the median; at approximately 80 years, there was a drop in wood density below the median for the entire population of the studied samples (Figure 2).

3.2. Compressive Strength of Spruce Wood

The resilience to compressive strength of wet wood (maximal moisture content, $Rc_{30\%}$) was between 4.58 [MPa] and 23.90 [MPa]. It can be assumed with 95% certainty that the resilience to the compressive strength of the wood with maximal saturation was between 13.99 [MPa] and 15.16 [MPa], and the coefficient of variation for this feature was 27.14% (Table 3).

Table 3. Statistical characteristics of resilience to compressive strength (Rc) of spruce wood (confidence interval 95%).

Variable	Mean	Confidence −95%	Confidence +95%	Minimum	Maximum	Standard Deviation	Coefficient of Variation
$Rc_{30\%}$ [MPa]	14.57	13.99	15.16	4.58	23.90	3.95	27.14
$Rc_{0\%}$ [MPa]	67.34	65.12	69.56	35.52	98.85	15.05	22.35

However, the resilience to compressive strength along the grain of dry wood ($Rc_{0\%}$) for spruce wood was much higher than that of wood with maximal saturation ($Rc_{30\%}$), which is a natural occurrence and is related to the submicroscopic structure of wood tissue and its affinity for water. The mean value of resilience to compressive strength of dry wood was 67.34 [MPa]. The indicated confidence interval allows us to conclude with 95% certainty that the mean for that value is within the range of 65.12–69.56 [MPa] (Table 3).

Figures 3 and 4 depict the radial variability of the compressive strength of wet wood (maximal moisture content, $Rc_{30\%}$) and dry wood ($Rc_{0\%}$). In the case of wet wood, there is an increase in the resilience to compressive strength until the age of 30; after turning 60, the resilience to compressive strength drops below the mean (Figure 3). A slightly different trend was observed for the dry wood (Figure 4). It reached the maximum resilience at the age of 60, after which there was a sudden drop in resilience, and it increased again at the age of 90–100, which maintained the mean values.

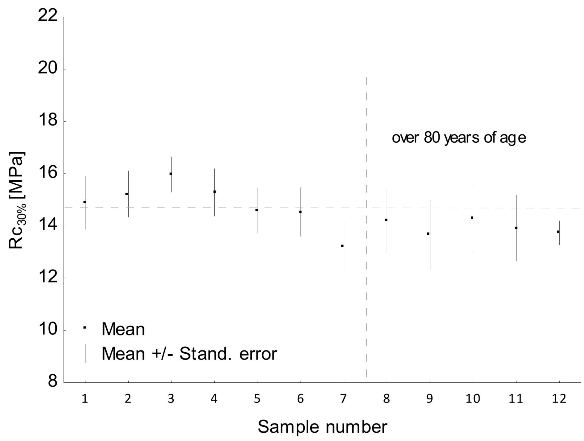

Figure 3. Radial variability of resilience to compressive strength of wet wood (maximal moisture content, $Rc_{30\%}$).

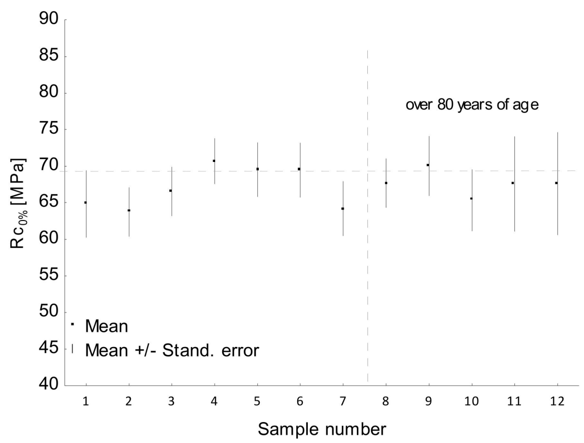

Figure 4. Radial variability of resilience to compressive strength of dry wood ($Rc_{0\%}$).

3.3. Bending Strength of Spruce Wood

The mean resilience to bending strength of maximally saturated wood ($Rg_{30\%}$) of the studied spruce wood was 59.81 [MPa] and dry wood 88.51 [MPa] (Table 4). It can be assumed with 95% certainty that the resilience to bending strength of saturated wood is in the range of 56.70 [MPa] to 62.80 [MPa], and the coefficient of variation was 69.70%. In the case of dry wood, it can be assumed with 95% certainty that the resilience to bending strength is in the range of 83.00 [MPa] to 94.00 [MPa] (Table 4).

Table 4. Statistical characteristics of resilience to bending strength (Rg) of spruce wood (confidence interval 95%).

Rg	Mean	Confidence −95%	Confidence 95%	Minimum	Maximum	Standard Deviation	Coefficient of Variation
$Rg_{30\%}$ [MPa]	59.81	56.70	62.80	11.20	35.10	86.20	69.70
$Rg_{0\%}$ [MPa]	88.51	83.00	94.00	17.70	47.30	126.40	70.10

Next, the radial variability of bending strength of dry wood ($Rg_{0\%}$) and wet wood (maximal saturation $Rg_{30\%}$) was analysed. The resilience of wet wood to bending was highly irregular (Figure 5). Close to the pith, the value is above the mean. At the age of about 30, there is a drop in the value for $Rg_{30\%}$ and only at over 80 years of age, particularly in youth up to about 10 years of age, there is a visible increased value of that feature.

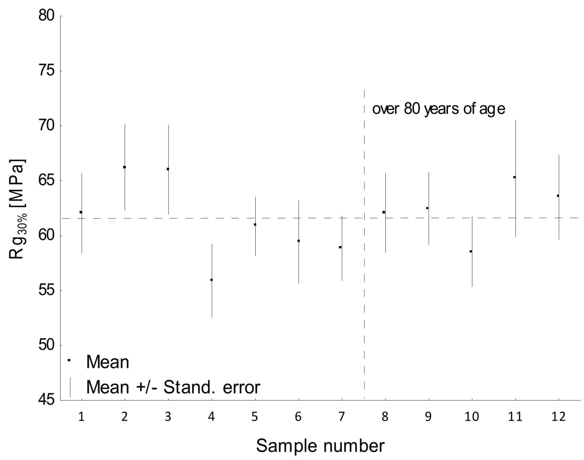

Figure 5. Radial variability of resilience to bending strength of wet wood (maximal moisture content $Rg_{30\%}$).

The bending strength of maximally saturated wood can experience significant fluctuations, which may have a considerable influence on the bending strength of spruce wood. This can be attributed to the submicroscopic and chemical structures of the wood. In the case of maximally saturated wood, the influence of secondary bonds in the cell membrane was negated, with primary bonding assuming a crucial function.

The trend in the variation in the strength of dry wood ($Rg_{0\%}$) was steadier (Figure 6). Until the age of 80 years, the values of $Rg_{0\%}$ were above the mean; however, over 80 years, there was a gradual decrease in the value of this wood property. This trend was not characteristic of coniferous species and may be a result of formulating structurally different wood in old trees.

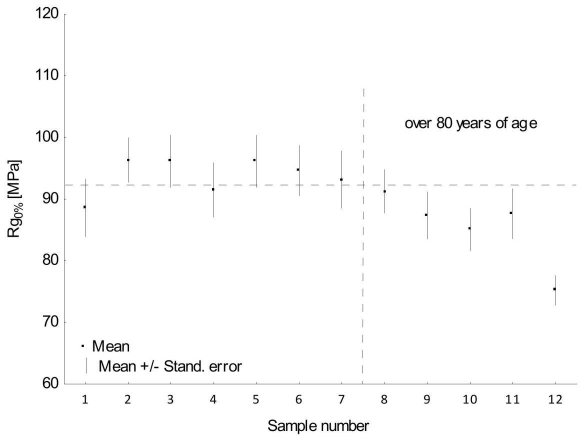

Figure 6. Radial variability of resilience to bending strength of dry wood ($Rg_{0\%}$).

3.4. Modulus of Elasticity of Wood in Bending

The mean value of the modulus of elasticity at static bending of maximally saturated wood ($E_{30\%}$) was 4105 MPa and that of dry wood ($E_{0\%}$) was 8940 MPa. It can be assumed with 95% certainty that modulus of elasticity for wet wood was in the range between 3915 MPa and 4295 MPa, whereas for dry wood, the range was between 8659 MPa and 9221 MPa.

The radial course of the variability in modulus of elasticity of spruce wood is shown in Figures 7 and 8. Generally, modulus of elasticity along the radius for maximally saturated wood was stable and similar to that of the meridian (Figure 7). Lower values for modulus of elasticity occurred in samples 1–4, that is, young wood, and then again in samples 9 and 10 (girth area). The modulus of elasticity was different for dry wood. The horizontal dotted line signifies values below the mean; samples 1 and 8–12 are below this line, which means that above the age of 80, there is a gradual decrease in modulus of elasticity of the dry wood (Figure 8). Similarly, as in the case of resilience to bending strength, this may be evidence of the changes caused by the ageing processes of trees.

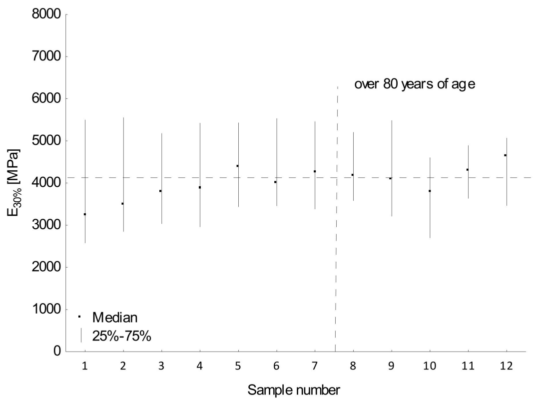

Figure 7. Radial variability of modulus of elasticity of maximally saturated wood ($E_{30\%}$).

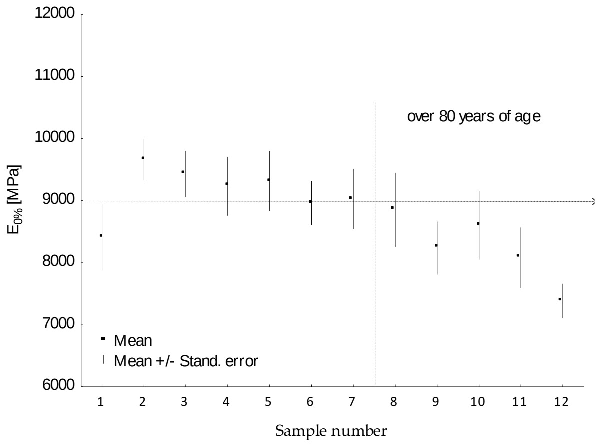

Figure 8. Radial variability of modulus of elasticity of dry wood ($E_{0\%}$).

3.5. Correlation of Tested Wood Properties

Table 5 presents the correlation coefficients between all the spruce wood properties analysed in this study. One of the most important physical properties of wood is its density. In the case of spruce wood, the value was positively correlated with a few of the mechanical wood properties, and the closest correlation was with the moduli of elasticity ($E_{30\%}$ = 0.489; $E_{0\%}$ = 0.350). There was no statistically significant correlation between wood density and resilience to the compressive strength of dry wood ($Rc_{0\%}$). A statistically significant but relatively low correlation was observed between wood density and its resilience to the bending strengths of maximally saturated wood ($Rg_{30\%}$), which questions the theory that wood density significantly and precisely reflects its mechanical properties. The results obtained do not fully confirm this hypothesis, at least in the case of spruce wood.

Table 5. Correlation coefficients ($p < 0.05$) of the studied properties of spruce wood.

Variable	q [kg/m^3]	$Rc_{30\%}$ [MPa]	$Rc_{0\%}$ [MPa]	$Rg_{0\%}$ [MPa]	$Rg_{30\%}$ [MPa]	$E_{30\%}$ [MPa]	$E_{0\%}$ [MPa]
q [kg/m^3]	1.000000	0.179389	0.092882	0.297543	0.194907	0.350029	0.489473
$Rc_{30\%}$ [MPa]	0.179389	1.000000	0.256814	0.249535	0.244464	0.060019	0.025485
$Rc_{0\%}$ [MPa]	0.092882	0.256814	1.000000	0.966643	0.083424	0.298453	0.221162
$Rg_{0\%}$ [MPa]	0.297543	0.249535	0.966643	1.000000	0.018171	0.273645	0.220698
$Rg_{30\%}$ [MPa]	0.194907	0.244464	0.083424	0.018171	1.000000	0.260696	0.116186
$E_{30\%}$ [MPa]	0.350029	0.060019	0.298453	0.273645	0.260696	1.000000	0.165693
$E_{0\%}$ [MPa]	0.489473	0.025485	0.221162	0.220698	0.116186	0.165693	1.000000

Red represents statistically significant ($p < 0.05$) correlation coefficients.

4. Discussion

This article describes the manner in which tree age affects the properties of wood tissue. The wood properties considered were wood density (q), resilience to bending strength (R_g), resilience to compressive strength (R_c), and modulus of elasticity (E), all of which were analysed at two extreme levels of wood moisture content, that is, dry wood and wet wood. At the same time, it was assumed that describing the variability of wood properties and correlating it with its age would determine the most suitable cutting age for the spruce, and it would indicate the optimal age limit for the technical quality of the produced wood.

The results of this study are particularly significant in the face of climate change, which is causing a massive dieback of forests, mainly spruce forests, in Europe [40,41]. The pace at which the spruce forest is dying leads to the assumption that in the foreseeable future, the spruce will retreat from the North European Plain and will be substituted with deciduous species, which even more strongly emphasises the relevance of the topic.

The heterogeneity of the wood properties of the trunk is interesting from the point of view of ecology, forest management, and the optimal use of wood resources. According to Fujimoto [42], as trees age, their wood becomes more ordered, and the ageing of trees from the perspective of variability in wood properties is clearly an irrevocable process. The results of this study provide clear guidelines for sustainable forest management and use of wood resources.

The variability of wood properties in relation to age has been studied for many trees and species, and has been described to some extent by Zobel et al. [43]. The age dependency of wood properties is difficult to comprehend fully because general patterns of variation differ among wood properties, even within the same tree. Changes in one wood property may cause subsequent changes to many other properties. For example, Dinwoodie [44] stated that with an increase in wood density, wood resilience increases as well, and its dimensional stability decreases.

In reference to Dinwoodie's observation [44], the obtained results reveal a very interesting phenomenon. There was a clear increase in resilience to bending strength ($R_{g30\%}$) and modulus of elasticity ($E_{30\%}$) in the girth layers of maximally saturated wood, and there was a decrease in density, resilience to bending strength ($R_{g0\%}$), and modulus of elasticity ($E_{0\%}$) of dry wood. At the same time, the limits of resilience to bending strength ($R_{g0\%}$) and modulus of elasticity ($E_{0\%}$) for dry wood indicate a link to wood density, which is confirmed by high correlation coefficients between these properties (they are 0.298 and 0.489, respectively, and are statistically significant with $p < 0.05$). A much lower correlation coefficient between wood density and resilience to compressive strength was noted in maximally saturated wood, whereas the correlation coefficients for resilience to compressive strength for dry wood ($R_{c0\%}$) were not statistically significant. It was also noted that wood density is clearly more correlated with the mechanical properties of dry wood than fully water-saturated wood. This indicates an important role in shaping the above-described relationships of the submicroscopic structure of wood, mainly crystalline and amorphous cellulose, and its affinity for water. This indicates that it is potentially possible to make a preliminary assessment of the proportion of crystalline and amorphous cellulose in spruce wood on the basis of desorption enhancement, i.e., the difference in strength between wet and maximally water-saturated wood.

The conducted studies confirmed the high variability of spruce wood properties in terms of radial distribution. A high dispersion of wood properties between the maximally saturated wood and dry wood was observed. This phenomenon is called desorption strengthening and is a result of the submicroscopic structure of the wood [45–47]. Most importantly, this phenomenon can be related to the chemical composition of wood, and to be more precise, the share and the form of hydrophilic cellulose and hemicellulose in wood tissue. Moreover, the ratio of crystalline cellulose to amorphous cellulose significantly affects this phenomenon. While amorphic cellulose is highly hygroscopic, crystalline cellulose is completely inaccessible to water [48]; thus, tracheid cell membranes become mechanically more resilient. In the analyses conducted, desorption strengthening in the girth areas of the spruce stem was observed. It is particularly easy to notice in the case of modulus of elasticity (E) and resilience to bending strength that wood properties are related to the ratio and type of cellulose in the tracheid membranes of wood [49,50]. Such significant differences in wood properties between dry wood and maximally saturated wood indicate a high content of amorphic cellulose in the girth of the studied trees, which occurs in the period when wood tissue is formed in older trees (above 80 years old).

The changes in the features and properties of wood with age can also be explained by the tree adaptive growth model, and in this case, the optimisation of vascular tissue, that is, the ratio of early wood in relation to water conditions which were subjected to a change. According to the "Pipe model theory" [51–54], there is a relationship between the size of the vascular tissue and the size of the assimilation apparatus. A tree that strives for a balance between the size of the assimilation apparatus, water accessibility in the soil, and the vascular tissue of the stem may react by widening or narrowing the early wood area in the annual ring in sapwood. Climate change and water deficits can cause water stress in trees. Considering the form of the root system of the spruce, it seems to be a species highly vulnerable to water stress. This might be a result of an attempt on the part of the spruce to adapt to long-term water deficit by narrowing the early wood in annual rings to avoid cavitation in the tracheids, that is, the formation of air bubbles obstructing water uptake and transport [55–57]. The process can be identified on the basis of variability in annual increment, and more precisely, the ratio of early wood in the annual ring which would allow determination of the moment water stress occurred and in reaction to it adequately anticipating mass dieback of trees and the occurrence of insect gradation. Drought and high temperatures are conducive to cavitation [58,59]. The process of formatting air congestion is also known as embolia [60] or air embolism [61,62], leading to the death of the tree. Scholars believe that developing resilience to cavitation is a key adaptive feature of trees and prevents drought-induced stress [63–66].

It can be assumed that trees, which protect themselves against cavitation, decrease the width of early wood in annual rings in favour of late wood; hence, in the stress period, there can be increased wood density in the girth [62]. A strong correlation was observed between hydraulic conductivity and primary wood density in coniferous species in cambial age [67,68].

In the analysis, spruce wood density increased, but only until the age of 60. After that age, the wood density on average decreased gradually; however, the resilience to compressive strength was preserved at a high level for both dry wood and maximally saturated wood. This can be linked to modifications in cell membranes which increase their stiffness and do not directly impact wood density.

The ageing process can also be considered from a different perspective. For example, perceiving the process as subjecting the xylem at the base of an ageing tree to various external factors, such as stress connected with growth. It is correct to assume that wood properties can change over time after its formation [42]. This view is supported by the increase in resilience to compressive strength, resilience to bending strength, and modulus of elasticity of maximally saturated wood, regardless of the wood density.

Hence, these studies indicate that the biomechanical functioning of trees described by, among others, Schniewind [69], Mencuccini et al. [70], and Sperry et al. [71] is directly connected to the mechanical and hydraulic properties of the anatomical elements of the tree tissue. These elements are optimised during the growth, development, and ageing of the trees. As a result of the external and internal factors affecting trees, numerous modifications in the tree tissue occur in order to reach a compromise between the mechanical and hydraulic properties of wood, which is a survival strategy.

5. Conclusions

The results of these studies indicate that spruce reaches its optimal technical quality of wood tissue at approximately 60 years old, which is about 20 years earlier than the previously assumed cutting age for this species in Central Europe. Climate change and water stress in recent decades have resulted not only in the dieback of spruce tree stands of older age classes, but also in an earlier technical maturation of spruce wood.

Considerable fluctuations were observed in the variability of the main wood of the studied spruces. Above 60 years of age, there was a decrease in wood density and resilience to the compressive strength of dry wood. Above 80 years of age, there was a significant drop in the resilience to bending strength and modulus of elasticity of dry wood. In the same age period, there was a visible increase in desorption strengthening, particularly in the case of static bending and modulus of elasticity, which can indicate that changes in the ultrastructural levels of wood are taking place, including a greater ratio of amorphic cellulose to crystalline cellulose. This is a significant finding not only for wood used in construction but also for the pulp and paper industry. Hence, it can be assumed with high probability that spruce ageing results in decreased wood properties and changes in wood tissues at many structural levels. An important conclusion of this study is that spruce wood density is not a good indicator of the mechanical properties of wood. Wood density, within a limited scope, is suitable for assessing technical quality. Moisture, at which wood properties are determined, has a significant impact on the relationship between density and wood resilience. The phenomenon of desorption strengthening mentioned in this article deserves more in-depth analysis, which can be a good indicator to determine the ratio of amorphic cellulose in wood, whose changes might be an expression of the tree ageing process.

Author Contributions: Conceptualization, T.J. and K.K.; methodology, T.J., A.T. and K.K.; software, T.J.; formal analysis, T.J. and K.K.; investigation, T.J., K.K. and B.N.; writing—original draft preparation, T.J., K.K., B.N., A.T., W.G., J.K. and J.S.; writing—review and editing, W.G., J.K., J.S., T.S. and D.G.; visualization, T.J., K.K., T.S. and D.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Dataset available on request from the authors.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lachowicz, H. Influence of location and age on the value of wood strength coefficients for silver birch (*Betula pendula* Roth.). *Sylwan* **2011**, *155*, 535–545.
2. Mańkowki, P.; Krzosek, S.; Andres, B. The susceptibility of Scots pine heartwood from various polish forestry regions to the brown rot fungus *Coniophora puteana* (Schumach.) P. Karst. *Drewno* **2020**, *63*, 206.
3. Plomion, C.; Leprovost, G.; Stokes, A. Wood formation in trees. *Plant Physiol.* **2001**, *127*, 1513–1523. [CrossRef] [PubMed]
4. Bernadzki, E. The age structure and the wood rot of old pine stands. *Sylwan* **2003**, *5*, 3–12.
5. Vacek, Z.; Prokůpková, A.; Vacek, S.; Cukor, J.; Bílek, L.; Gallo, J.; Bulušek, D. Silviculture as a tool to support stability and diversity of forests under climate change: Study from Krkonoše Mountains. *Cent. Eur. For. J.* **2020**, *66*, 116–129. [CrossRef]
6. Vacek, Z.; Vacek, S.; Cukor, J. European forests under global climate change: Review of tree growth processes, crises and management strategies. *J. Environ. Manag.* **2023**, *332*, 117353. [CrossRef]
7. Zeidler, A.; Borůvka, V.; Brabec, P.; Tomczak, K.; Bedřich, J.; Vacek, Z.; Cukor, J.; Vacek, S. The possibility of using non-native spruces for Norway Spruce wood replacement—A case study from the Czech Republic. *Forests* **2024**, *15*, 255. [CrossRef]
8. Cukor, J.; Vacek, Z.; Vacek, S.; Linda, R.; Podrázský, V. Biomass productivity, forest stability, carbon balance, and soil transformation of agricultural land afforestation: A case study of suitability of native tree species in the submontane zone in Czechia. *Catena* **2022**, *210*, 105893. [CrossRef]
9. Borecki, T.; Orzechowski, M.; Stępień, E.; Wójcik, R. Expected impact of climate change on forest ecosystems and its consequences in forest management planning. *Sylwan* **2017**, *161*, 531–538.
10. Shukla, P.R.; Skeg, J.; Buendia, E.C.; Masson-Delmotte, V.; Pörtner, H.-O.; Roberts, D.C.; Zhai, P.; Slade, R.; Connors, S.; van Diemen, S.; et al. *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas Fluxes in Terrestrial*; IPCC: Geneva, Switzerland, 2019.
11. Kharuk, V.I.; Im, S.T.; Dvinskaya, M.L. Decline of spruce (*Picea abies*) in forests of Belarus. *Russ. J. Ecol.* **2016**, *47*, 241–248. [CrossRef]
12. Toth, D.; Maitah, M.; Maitah, K.; Jarolínová, V. The impacts of calamity logging on the development of spruce wood prices in czech forestry. *Forests* **2020**, *11*, 283. [CrossRef]
13. Jyske, T.; Harri Mäkinen, H.; Saranpää, P. Wood density within Norway Spruce stems. *Silva Fenn.* **2008**, *42*, 439–455. [CrossRef]
14. Netherer, S.; Schopf, A. Potential effects of climate change on insect herbivores in European forests—General aspects and the pine processionary moth as specific example. *For. Ecol. Manag.* **2010**, *259*, 831–838. [CrossRef]
15. Brzeziecki, B.; Keczyński, A.; Zajączkowski, J.; Drozdowski, S.; Gawron, L.; Buraczyk, W.; Bielak, K.; Szeligowski, H.; Dzwonkowski, M. Threatened tree species of the Białowieża National Park (the Strict Reserve). *Sylwan* **2012**, *156*, 252–261.
16. Drozdowski, S.; Brzeziecki, B.; Żybura, H.; Żybura, B.; Gawron, L.; Buraczyk, W.; Zajączkowski, J.; Bolibok, L.; Szeligowski, H.; Bielak, K.; et al. Long−term dynamics of old−growth stands in the managed part of the Białowieża Forest: Increasing and declining tree species. *Sylwan* **2012**, *156*, 663–671.
17. Mauer, O.; Palátová, E. Decline of Norway spruce in the Krkonoše Mts. *J. For. Sci.* **2010**, *56*, 361–372. [CrossRef]
18. Šrámek, V.; Vejpustková, M.; Novotný, R.; Hellebrandová, K. Yellowing of Norway spruce stands in the Silesian Beskids–damage extent and dynamics. *J. For. Sci.* **2008**, *54*, 55–63. [CrossRef]
19. Svoboda, M.; Fraver, S.; Janda, P.; Bače, R.; Zenáhlíková, J. Natural development and regeneration of a Central European montane spruce forest. *For. Ecol. Manag.* **2010**, *260*, 707–714. [CrossRef]
20. Brůna, J.; Wild, J.; Svoboda, M.; Heurich, M.; Müllerova, J. Impacts and underlying factors of landscape-scale, historical disturbance of mountain forest identified using archival documents. *For. Ecol. Manag.* **2013**, *305*, 294–306. [CrossRef]
21. Pötzelsberger, E.; Spiecker, H.; Neophytou, C.; Mohren, F.; Gazda, A.; Hasenauer, H. Growing non-native trees in european forests brings benefits and opportunities but also has its risks and limits. *Curr. For. Rep.* **2020**, *6*, 339–353. [CrossRef]

22. Vacek, Z.; Cukor, J.; Vacek, S.; Linda, R.; Prokůpková, A.; Podrázský, V. Production potential, biodiversity and soil properties of forest reclamations: Opportunities or risk of introduced coniferous tree species under climate change? *Eur. J. For. Res.* **2021**, *140*, 1243–1266. [CrossRef]
23. Wimmer, R.; Grabner, M. A comparsion of tree-ring features in Picea abies as correlated with climate. *JAWA J.* **2000**, *21*, 403–416.
24. James, K.R.; Haritos, N.; Ades, P.K. Mechanical stability of trees under dynamic loads. *Am. J. Bot.* **2006**, *93*, 1522–1530. [CrossRef] [PubMed]
25. Šilinskas, B.; Varnagirytė-Kabašinskienė, I.; Aleinikovas, M.; Beniušienė, L.; Aleinikovienė, J.; Škėma, M. Scots Pine and Norway Spruce Wood Properties at Sites with Different Stand Densities. *Forests* **2020**, *11*, 587. [CrossRef]
26. Treacy, M.; Dhubháin, A.N.; Evertsen, J. The influence of microfibril angle on modulus of elasticity and modulus of rupture in four provenances of Irish grown Sitka spruce (*Picea sitchensis* (Bong.) Carr). *J. Inst. Wood Sci.* **2000**, *15*, 211–220.
27. Mclean, J.P.; Evans, R.; Moore, J.R. Predicting the longitudinal modulus of elasticity of Sitka spruce from cellulose orientation and abundance. *Holzforschung* **2010**, *64*, 495–500. [CrossRef]
28. Moore, J. *Wood Properties and Uses of Sitka Spruce in Britain*; Research Report-Forestry Commission: Edinburgh, UK, 2011.
29. Jelonek, T.; Klimek, K.; Kopaczyk, J.; Wieruszewski, M.; Arasimowicz-Jelonek, M.; Tomczak, A.; Grzywiński, W. Influence of the tree decay duration on mechanical stability of Norway spruce wood (*Picea abies* (L.) Karst.). *Forests* **2020**, *11*, 980. [CrossRef]
30. Verkasalo, E.; Leban, J.M. MOE and MOR in static bending of small clear specimens of Scots pine, Norway spurce and European fir from Finland and France and their prediction for the comparison of wood quality. *Pap. Ja Puu* **2002**, *84*, 332–340.
31. Bacher, M.; Krzosek, S. Modulus of elasticity tension/bending ratio of polish grown pine (*Pinus sylvestris* L.) and spruce (*Picea abies* Karst.) timber. *Ann. Warsaw Univ. Life Sci. SGGW. For. Wood Technol.* **2013**, *82*, 31–38.
32. Mclean, J.P. Wood Properties of Four Genotypes of Sitka Spruce. Ph.D. Thesis, Department of Analytical and Environmental Chemistry, University of Glasgow, Glasgow, UK, 2008.
33. Kraft, G. *Beiträge zur Lehre von den Durchforstungen, Schlagstellungen und Lichtungshieben*; Klindworth: Hannover, Germany, 1884; pp. 85–130.
34. Van Laar, A.; Akça, A. *Forest Mensuration*; Springer: Dordrecht, The Netherlands, 2007; pp. 95–147.
35. *ISO 13061-2:2014*; Physical and Mechanical Properties of Wood—Test Methods for Small Clear Wood Specimens. Part 2: Determination of Density for Physical and Mechanical Tests. International Organization for Standardization: Geneva, Switzerland, 2014.
36. *ISO 13061-17:2017*; Physical and Mechanical Properties of Wood—Test Methods for Small Clear Wood Specimens Part 17: Determination of Ultimate Stress in Compression Parallel to Grain. International Organization for Standardization: Geneva, Switzerland, 2017.
37. *ISO 3129:2019*; Wood-Sampling Methods and General Requirements for Physical and Mechanical Testing of Small Clear Wood Specimens. International Organization for Standardization: Geneva, Switzerland, 2019.
38. *PN-EN 380:1998*; Timber Structures—Test Methods—General Principles for Static Load Testing. European Committee for Standardization: Brussels, Belgium, 1998.
39. *ASTM D143-94*; Standard Test Methods for Small Clear Specimens of Timber. ASTM International: West Conshohocken, PA, USA, 2000.
40. Senf, C.; Buras, A.; Zang, C.S.; Rammig, A.; Seidl, R. Excess forest mortality is consistently linked to drought across Europe. *Nat. Commun.* **2020**, *11*, 6200. [CrossRef]
41. Neumann, M.; Mues, V.; Moreno, A.; Hasenauer, H.; Seidl, R. Climate variability drives recent tree mortality in Europe. *Glob. Change Biol.* **2017**, *23*, 4788–4797. [CrossRef] [PubMed]
42. Fujimoto, T. Evaluation of the age dependent variation of wood properties based on the eigenvalue distribution of near infrared spectra. *Chem. Int. Lab. Syst.* **2022**, *225*, 104576. [CrossRef]
43. Zobel, B.J.; Van Buijtenen, J.P. *Wood Variation: Its Causes and Control*; Springer Science & Business Media: New York, NY, USA, 2012.
44. Dinwoodie, J.M. *Timber: Its Nature and Behaviour*; CRC Press: Boca Raton, FL, USA, 2000.
45. Gu, H.; Zink-Sharp, A.; Sell, J. Hypothesis on the role of cell wall structure in differential transverse shrinkage of wood. *Holz Als Roh-Und Werkst.* **2001**, *59*, 436–442. [CrossRef]
46. Hématy, K.; Höfte, H. Cellulose and cell elongation. The expanding cell. *Plant. Cell. Monogr.* **2007**, *6*, 33–56.
47. Krauss, A. Ultrastrukturalne uwarunkowania wybranych właściwości mechanicznych drewna sosny i świerku. *Rozpr. Nauk. UP Pozn.* **2010**, *406*, 1–115.
48. Astley, R.J.; Harrington, J.J.; Stol, K.A. Mechanical modelling of wood microstructure, an engineering approach. *IPENZ Trans.* **1997**, *24*, 21–29.
49. Winandy, J.; Rowell, R. *The Chemistry of Wood Strength. Handbook of Wood Chemistry and Wood Composites*, 2nd ed.; CRC Press: Boca Raton, FL, USA, 1984.
50. Xi, E. Dynamic relationship between mechanical properties and chemical composition distribution of wood cell walls. *Wood Res.* **2018**, *63*, 179–192.
51. Shinozaki, K.; Yoda, K.; Hozumi, K.; Kira, T. A quantitative analysis of plant form-the pipe model theory: I. Basic analyses. *Jpn. J. Ecol.* **1964**, *14*, 97–105.
52. Shinozaki, K.; Yoda, K.; Hozumi, K.; Kira, T. A quantitative analysis of plant form-the pipe model theory: II. Further evidence of the theory and its application in forest ecology. *Jpn. J. Ecol.* **1964**, *14*, 133–139.

53. Jelonek, T.; Pazdrowski, W.; Arasimowicz, M.; Tomczak, A.; Walkowiak, R.; Szaban, J. The applicability of the pipe model theory in trees of Scots pine (*Pinus sylvestris* L.) of Poland. *J. For. Sci.* **2008**, *54*, 519–531. [CrossRef]
54. Lehnebach, R.; Beyer, R.; Letort, V.; Heuret, P. The pipe model theory half a century on: A review. *Ann. Bot.* **2018**, *121*, 773–795. [CrossRef] [PubMed]
55. Zimmermann, M.H.; Brown, C.L. *Trees: Structure and Function*; Springer: Berlin/Heidelberg, Germany, 1971.
56. Jackson, G.E.; Irvine, J.; Grace, J. Xylem cavitation in Scots pine and Sitka spruce saplings during water stress. *Tree Physiol.* **1995**, *15*, 783–790. [CrossRef]
57. Rosner, S.; Karlsson, B.; Konnerth, J.; Hansmann, C. Shrinkage processes in standard-size Norway spruce wood specimens with different vulnerability to cavitation. *Tree Physiol.* **2009**, *29*, 1419–1431. [CrossRef] [PubMed]
58. Boisvenue, C.; Running, S.W. Impacts of climate change on natural forest productivity–evidence since the middle of the 20th century. *Glob. Chang. Biol.* **2006**, *12*, 862–882. [CrossRef]
59. Adam, H.D.; Zeppel, M.J.B.; Anderegg, W.R.L.; Hartmann, H.; Landhäusser, S.M.; Tissue, D.T.; Huxman, T.E.; Hudson, P.J.; Franz, T.E.; Allen, C.D.; et al. A multispecies synthesis of physiological mechanisms in drought−induced tree mortality. *Nat. Ecol. Evol.* **2017**, *1*, 1285–1291. [CrossRef]
60. Roloff, A. *Bäume. Lexikon der praktischen Baumbiologie*; WILEY_VCH Verlag GmbH & Co. KGaA: Weinheim, Germany, 2010.
61. Martin-Benito, D.; Anchukaitis, K.J.; Evans, M.N.; Del Río, M.; Beeckman, H.; Cańellas, I. Effects of drought on xylem anatomy and water−use efficiency of two co−occurring pine species. *Forests* **2017**, *8*, 322. [CrossRef]
62. Rosner, S. Wood density as a proxy for vulnerability to cavitation: Size matters. *J. Plant Hydr.* **2017**, *4*, e001. [CrossRef]
63. Jacobsen, A.; Pratt, B.; Ewers, F.; Davis, S. Cavitation resistance among 26 Chaparral species of Southern California. *Ecol. Monographs.* **2007**, *77*, 99–115. [CrossRef]
64. Choat, B.; Jansen, S.; Brodribb, T.J.; Cochard, H.; Delzon, S.; Bhaskar, R.; Bucci, S.J.; Field, T.S.; Gleason, S.M.; Hacke, U.G.; et al. Global convergence in the vulnerability of forests to drought. *Nature* **2012**, *491*, 752–755. [CrossRef]
65. Cochard, H.; Delzon, S. Hydraulic failure and repair are not routine in trees. *Ann. For. Sci.* **2013**, *70*, 659–661. [CrossRef]
66. Bruchwald, A.; Dmyterko, E.; Bałazy, R. Risk model of tree stand damage by winds and its evaluation based on damage caused by cyclone 'Xaver'. *For. Syst.* **2018**, *27*, 2. [CrossRef]
67. Domec, J.C.; Warren, J.M.; Meinzer, F.C.; Lachenbruch, B. Safety for xylem failure by implosion and air-seeding within roots, trunks and branches of young and old conifer trees. *IAWA J.* **2009**, *30*, 101–120. [CrossRef]
68. Rosner, S.; Světlík, J.; Andreassen, K.; Børja, I.; Dalsgaard, L.; Evans, R.; Karlsson, B.; Tollefsrud, M.M.; Solberg, S. Wood density as a screening trait for drought sensitivity in Norway spruce. *Can. J. For. Res.* **2014**, *44*, 154–161. [CrossRef]
69. Schniewind, A.P. Horizontal specifi c gravity variation in tree stems in relations to their support function. *For. Sci.* **1962**, *8*, 111–118.
70. Mencuccini, M.; Grace, J.; Fioravanti, M. Biomechanical and hydraulic determinants of tree structure in Scots pine: Anatomical characteristics. *Tree Physiol.* **1997**, *17*, 105–113. [CrossRef]
71. Sperry, J.S.; Hacke, U.G.; Pittermann, J. Size and function in conifer tracheids and angiosperm vessels. *Am. J. Bot.* **2006**, *93*, 1490–1500. [CrossRef]