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Woodland Management Practices in Bronze Age, Bruszczewo, Poland

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Abstract: The article presents a study of wood excavated from archaeological site in Poland (2100–1650 BC). The large amount of collected samples created a unique opportunity for research because the subfossil wood was in very good preservation state. This made it possible to carry out dendrotypological analysis. This is the first such study conducted for Early Bronze Age timber originating from Poland. The main goal of the study was to determine whether the presence of strong and abrupt reductions and releases of growth, observed within tree-ring sequences, is due to natural stand dynamics, results from the influence of extreme environmental factors or whether they should be linked to specific silvicultural practices already known in ancient times. Another purpose of the study was to determine the type of forest management techniques applied to the trees growing in Bruszczewo site. The research was conducted using the dendrochronological method. In addition to the measurements of growth-ring width, the development of earlywood and latewood zones, the proportion of sapwood and the presence of specific features of tree trunks were analysed. A detailed study allowed identifying the samples originating from coppiced and shredded trees. A characteristic feature of the trees subjected to these silvicultural practices is the presence of strong and abrupt reductions and releases of growth. Moreover, coppiced trees were specified by the large proportion of sapwood in the cross-section of the stem, reduced number of sapwood rings, small and numerous earlywood vessels, diminished earlywood vessels area. In turn, shredded trees distinguished themselves by a strong reduction in the earlywood width in the years following the shredding event. The research of archaeological wood from the ancient settlement proves that during the Early Bronze Age various forest management techniques were used in this site. These treatments were aimed at improving the quality and quantity of the raw material harvested from forest areas.

Keywords: dendroecology; dendrotypology; coppicing; pollarding; shredding; silvicultural techniques

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1. Introduction

This paper presents analysis of wood from the archaeological site 5 of the Early Bronze Age (EBA) excavations in Bruszczewo, district Kościan in Greater Poland, 60 km south of Poznań. The site is used during two phases of the Bronze Age with a hiatus in between. These phases are the Early Bronze Age Phase from 2100 to 1650 BC and the Late Bronze Age/Early Iron Age Phase from 1000 to 500 BC. In the EBA Phase, Bruszczewo was one of the few fortified settlements and part of the Únětice Culture, the first in a larger amount metal processing community in central Europe. The long and intensive research by a team of archaeologists, archaeozoologists, archaeobotanists and geologists among others, allows the reconstruction of the settlement, its fortifications and houses, as well as the environmental, nutrition and living conditions of the EBA people [1–4]. Palynological analyses pointed to a substantial transformation of the natural environment by people living in this territory [5]. Previous dendrological studies revealed that various wood taxa were selected for different utilitarian purposes [6]. Dendrochronological measurements enabled for the identification of single building activities in the years between 1790 and 1787 BC, when the lake-side fortification was erected [7–9].

During this former work on the material from the Bruszczewo site, it was found that the wood had characteristics that would indicate the intentional use of various silvicultural practices to obtain the appropriate quality and quantity of usable products. Hence, questions arose: Did the EBA people had already 3900 years ago the knowledge of forest management techniques as coppicing and shredding? And how intense was their cultivation of the forest? These were the research questions this article aims to answer.

Coppicing and pollarding (including shredding) were commonly used techniques during the ancient times (Figure 1). These forest management practices aimed at obtaining the appropriate quality and quantity of wood, timber and leaf-fodder for livestock. Coppice is believed to be applied at least since the Neolithic, and it was a very popular and widespread woodland management system during medieval and post-medieval times in most parts of Europe, up to the first half of the 20th century [10–12]. Archaeological studies suggest that pollarding has occurred since at least the Neolithic period as well [13].

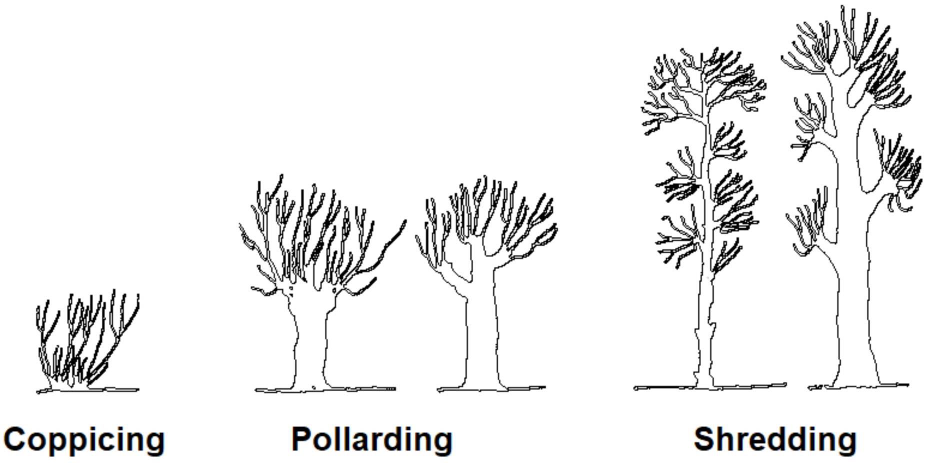

Figure 1. Woodland management systems. Based on a drawing prepared by [14].

The main goal of coppice and coppice-with-standards management systems was to provide an appropriate amount of wood for construction and fuel, as well as to deliver fodder for domesticated animals. Coppices supplied wood for many purposes, especially charcoal for metal smelting [15]. The other aim of coppicing was the production of long, straight and uniform poles and stems for fences, hurdles and building construction [16]. The shoots obtained from coppiced trees were also used in their young stage of growth for interweaving in wattle fencing (as is the practice with coppiced willows and hazel) [17]. Coppicing can be applied to most of the broad-leaved woody plants such as oak (*Quercus* L.), elm (*Ulmus* L.), ash (*Fraxinus* L.), maple (*Acer* L.), lime (*Tilia* L.), birch (*Betula* L.), alder (*Alnus* Mill.), beech (*Fagus* L.), hornbeam (*Carpinus* L.), willow (*Salix* L.), poplar (*Populus* L.), rowan (*Sorbus* L.), hazel (*Corylus* L.), hawthorn (*Crataegus* L.), blackthorn (*Prunus spinosa* L.), holly (*Ilex* L.) and sweet chestnut (*Castanea sativa* Mill.) [13]. Coppicing results in a faster radial growth during the first years of life compared to normal tree development which is characterised by smaller rings. Such a way of growth-ring formation also has some implications regarding the mechanical properties of wood. For example, the timber from fast-grown oaks is usually of the high-density type. This is because the amount of the denser latewood increases along with the total ring width enlargement. High-density oak timber has better strength properties compared to low-density wood. Therefore, during the construction of the storage houses, fast-grown oaks were preferred [18]. Moreover, coppicing allows achieving a sustainable supply of relatively thin diameter stems in relatively short time and maximises the wood production volume from the stand [17,19]. All these features would be beneficial for obtaining appropriate properties of the timber used for the construction of wooden structures within the Bruszczewo settlement.

The second type of this forest management practice, that is coppice with standards, was used for pig breeding [20]. In this system, some trees were allowed to grow bigger, and they provided the timber for building construction and also delivered acorns to feed the pigs [17]. This usage of forest products is also supported by macro finds which show that a large number of acorns from probably sweet oaks were found in the Bruszczewo settlement, and they were most probably also consumed by humans [6,21]. In addition to this, coppiced trees were used to obtain leaf fodder for domesticated animals [16].

Coppiced hardwoods were used extensively in carriage construction and shipbuilding, and they are still sometimes cultivated for the production of wooden buildings and furniture. Moreover, withies for wickerwork are grown in coppices of various willow species, principally osier. In Europe, chestnut trees are coppiced for the use as canes and batons for the martial art of the same name. Coppicing may be practised to encourage specific growth patterns, as is in the case of cinnamon trees which are grown for their bark. Some eucalyptus species are coppiced too [17].

A similar situation occurred in the case of shredding practices. In prehistoric times, shredded trees were an essential source of fodder for many stock animals [13]. Pollarding (a system that embraces shredding) increases the production of leafy material and makes it easier to harvest the trees. Moreover, as a result of pollarding, the leaves cannot be reached by freely-grazing animals [16]. Cutting leaf-fodder for livestock is reported in written sources from the Roman times. Many tree species including elm, ash, rowan, but also hazel, hawthorn and even conifers were cut as fodder throughout Central and Western Europe. However, ash, elm and oak were particularly valuable [13]. The use of leaves as fodder is proven by the large amount of ivy and mistletoe pollen in the lake profile close to the Bruszczewo settlement. This large number of ivy and mistletoe has been interpreted as evidence for feeding animals with leaves in the Early Bronze Age phase, as they normally are not visible in the pollen spectrum [5].

Pollarding and shredding were undertaken to provide the feed for direct consumption, but the leaves of the trees were also important for winter forage [13]. Most probably, harvesting took place in July and August, and afterwards the leaves were dried and stored for the use during the winter months [16]. However, the timing of harvesting may also have been different. The presence of mistletoe and ivy pollen in the lake profiles indicates that the plants were delivered to the settlement during the flowering phase. Mistletoe blooms from January to April and ivy flowers in November and December. Thus, they could be harvested during these months both to replenish forage supplies and to provide fresh food at the end of winter when previous stocks were depleted [5].

In addition to this, trees were lopped for litter. The leaves of trees also served as fertilisers. In addition, pollards provided a valuable supply of fencing poles, fences, stakes and crooked timber for farmers. Pollards were also used for producing firewood, fuel, charcoal and constructional wood [13]. Moreover, branches were also exploited to weave baskets. This was in the case of Bruszczewo settlement, as evidenced by discovered basket identified as a fish trap [8].

Pollarding in wood-pastures is a traditional management system for broad-leaved forests. It has been in widespread use for centuries throughout Central and Western Europe. Grazed woodlands were usually composed of ancient trees that had grown in open spaces utilised for cattle pastures. These areas were traditionally treated as a source of pasturage, fuel, timber and other forest products [22]. Nowadays, pollarding and shredding are applied in order to gather ligneous matter, mainly for heating purposes [23]. These practices increase the production of firewood [13].

Nevertheless, all these forest management techniques, despite their high popularity in the past, started to lose the significance, and became less and less practised. The areas occupied by semi-natural woodland types that were the result of coppicing and pollarding, have been dramatically reduced since the mediaeval times. Coppicing and pollarding were gradually abandoned in North-Western and Central Europe by the mid-20th century. The discontinuation of their usage contributed to substantial landscape transformation and habitat changes. The resignation from coppicing and pollarding had a significant impact on forests' biodiversity and resulted in the decline of entire herb layer communities as well as the vanishing of some plant and animal species. The change of land use had an adverse effect on some species, especially in the case of the trees that require sufficient amount of sunlight for their successful regeneration [10,24,25]. Currently, in most territories of Northern, Western and Central-Eastern Europe, less than 1% of the forest area is occupied by coppice woodlands. In contrast to this, more than 10% of these woodlands occur in Greece, Italy, France, Bulgaria, Hungary, Spain, Portugal, Luxembourg, Belgium and Slovenia [26].

The aim of the presented research was to investigate the cause of the formation of the unusual growth-ring structure in wood from the Bruszczewo site. In this wood, zones of strong and abrupt reductions and releases of growth were very common. The main goal of the study was to determine whether the presence of these zones is due to natural stand dynamics, results from the influence of extreme environmental factors or whether they should be associated with the exploitation of certain silvicultural practices during ancient times.

Wood from archaeological excavations is usually used for dating wooden objects. It is also often applied for palaeoclimatic reconstructions and only occasionally serves as material for dendroecological research. However, it is extremely rare that archaeological wood provides information on ancient forest management techniques [27]. Detailed examination of the wood structure, development of growth-rings, variation in ring width and cell anatomical formation allows to interpret the methods used by people living in prehistoric times to harvest timber and other forest products. This article presents the first analysis of this type carried out in Poland for wood from the Early Bronze Age (2100–1650 BC).

The Bruszczewo site offers a unique opportunity for dendrotypological research. Early Bronze Age wood is rarely found in archaeological excavations because specific conditions of the sedimentary environment are required to preserve the plant remains in a subfossil state. The large amount of wood samples collected during the Bruszczewo archaeological works is therefore an exception on an international scale. This makes the material all the more worthy of detailed research and comprehensive elaboration of the results.

2. Materials and Methods

The Bruszczewo site (52°00′41″ N, 16°34′05″ E) is located in the Kościan district in Greater Poland, 60 km south of Poznań (Figure 2). The settlement is situated on a spur of an ice-age moraine hilltop, which protrudes into the now silted-up lake. The lake is still preserved today as a lowland bog through which the canalised river Samica flows. In the Early Bronze Age, the site was separated from the hinterland to the north and west by an elaborate ditch-wall system and up to three rows of palisades. To the south and east towards the lake stood a three-row fortification of two wattle walls (fascine) and sectional beam walls. These fortifications served both as defence against enemies and as protection against flooding, since rising water levels could cause a serious problem for the houses directly on the lake shore. The original proximity to the lake and the present-day lowland bog provided the best preservation conditions for organic and thus also timber material [7–9].

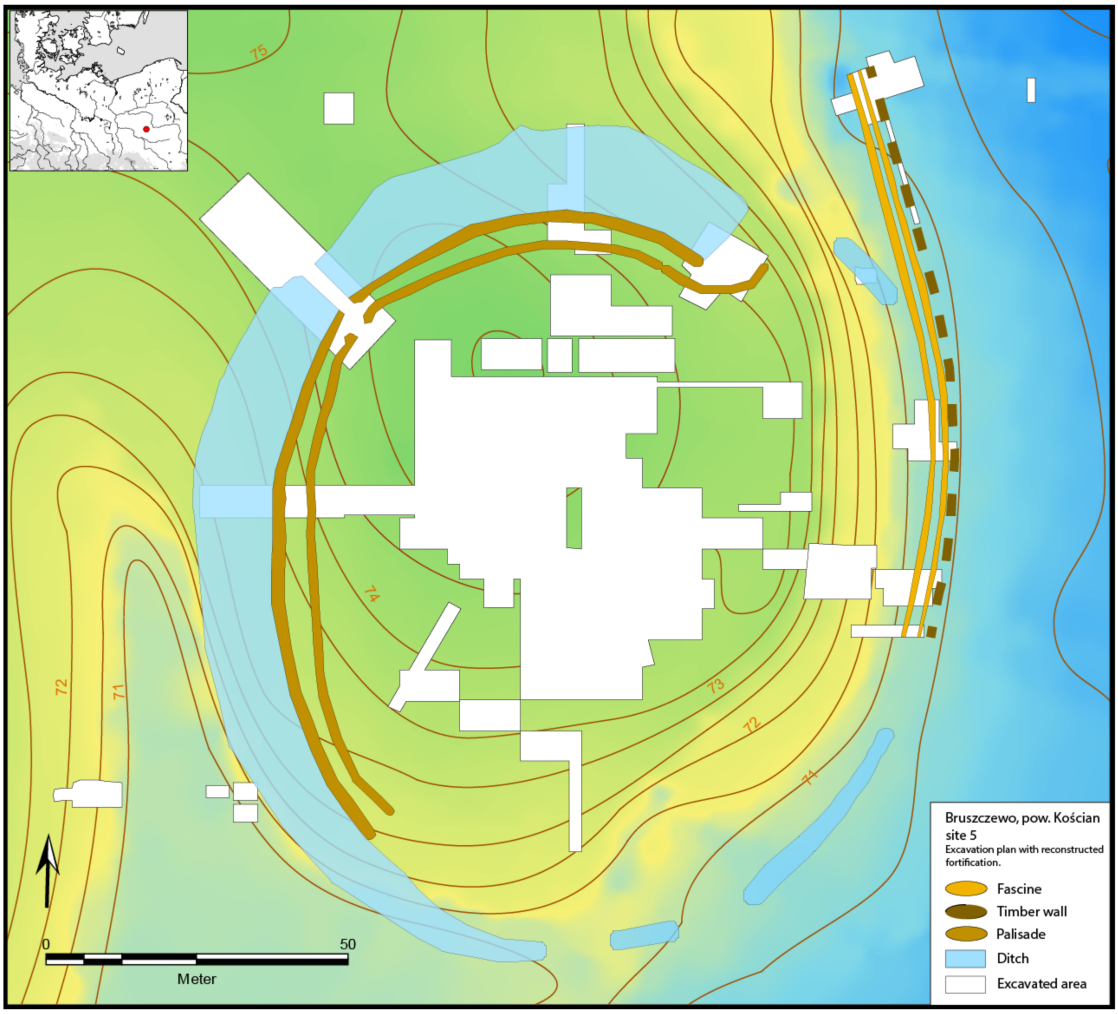

Figure 2. Bruszczewo plan.

The construction of the lakeside fascine took place in a relatively short time horizon—1890–1889 cal BC. During archaeological excavations it was observed that two wattle walls were exposed over a length of 28 m. Three rows of palisades consisting of beams formed in sections, with a maximum height of up to 2 m of the pales was also visible. Geophysical surveys showed that this fortification runs along the entire lakeshore for a length of at least 170 m (Figure 2). This leads to the conclusion that the demand for wood and wickerwork must have been enormous. It has been estimated that about 600 to over 1000 pales (all sharpened and over 2 m long) for all three rows of fortification were used. In turn, for the two fascines with wattle the timber with a total length of about 3.4 km of branches was required. As a result of previous dendrochronological analysis, it was also noted that at one point there was a shortage of useful wood to make the fascines on the lake side and, for example, a pale of willow or poplar instead of oak were used for construction (personal communication Tomasz Ważny). All this proves that the acquisition of such a large amount of timber needed appropriate logistic and that the planning and organisation of the construction of these wooden structures had to be started well in advance. These facts suggest also that the inhabitants of the Bruszczewo settlement may have applied special forest techniques and farming systems in order to obtain sufficient amount of wood.

During the archaeological works at the Bruszczewo site about two thousand wood samples were excavated. Some of them belong to house sub-construction or were pales for the houses. The pales show cutmarks of axes and the width of the cutting marks was conform to the width of the found bronze axes. The pales are entirely documented in [6]. Other wood originated from stems and branches used for the fascine (wattle fence) construction. Some artefacts such as many pieces of fatwood (kindling), a weaving sword and a wooden ball were found as well. The use and workmanship of wood was on a high standard as proven by previous research (personal communication Tomasz Ważny). The majority of material from the Bruszczewo site was preserved in the form of tiny pieces of wood (Figure 3). Such small fragments do not allow the dendrochronological analyses. Therefore, only 190 samples were selected for the conduction of this study. The wood intended for the analysis was marked by the presence of at least a dozen or so annual growth-rings.

Figure 3. Wood samples excavated at Bruszczewo site.

Wood excavated at the Bruszczewo settlement was collected from waterlogged deposits. Due to the wet conditions the preservation of the Early Bronze Age timber was exceptionally good. Nevertheless, in most of the cases, the wood selected for analysis distinguished itself by an advanced stage of the destruction process. The degradation of wood manifested itself macroscopically by distinctly diminished hardness and change in colour. In turn, drying and shrinkage of the wood proceeded as a consequence of the high summer temperatures affecting the wood during archaeological excavations. Fortunately, only some of the samples were heavily crushed and deformed. Simultaneously, the microscopic observations showed a significant reduction in the thickness of cell walls, resulting from the partial decay of wood tissue during the sedimentation time. Even though a substantial degree of wood decomposition was visible, the internal structure of wooden tissue was usually appropriate for dendrochronological works.

The samples chosen for the research were cut into stem discs or disc fragments, and then frozen to increase the hardness of the wood. The top layer of wood was removed using a knife to reveal growth-rings more clearly. The samples prepared in this manner were subjected to dendrochronological measurements. For this purpose, the LINTAB device and TSAP Win computer program [28] were used. The width of the growth-ring was measured to the nearest 0.01 mm. The number of rings was also obtained. Taxonomic identification of the wood was performed on the basis of wood anatomy atlases [29,30]. Visual analysis of the wood structure was carried out under up to 200 times microscope magnification.

During research special attention was paid to the way of the wood structure development and to the trends that were visible in growth-ring sequences. The incidence of all disturbances in the growth-ring series was also noted. Moreover, the occurrence of sapwood zone and number of sapwood rings was determined, and the percentage of sapwood area was calculated as the sum of the sapwood rings width in relation to the total width of all rings in the sample. The presence of the pith or double pith, the existence of outermost ring or the shape of cross-section of the stem were defined as a result of macro and microscopic observations. On the basis of the curvature of growth-rings and the divergence of the medullary rays the distance to the pith and number of eventually missing innermost rings were established. Furthermore, all deviations from the normal structure of earlywood and latewood zones were identified with application of simple visual inspections. On this basis various anatomical wood features were determined, including small, separated and numerous earlywood vessels, the reduced number of rows of earlywood vessels, narrow or wide earlywood and latewood zones. The analysis of earlywood also embraced the calculation of its percentage within each growth-ring. The determination of the percentage of earlywood was accomplished by relating the width of the earlywood zone to the total width of the growth-ring. The next step was to identify the growth-rings with a significant deviation in the proportion of earlywood. For this purpose, measurement series were examined for the presence of sequences of two to three adjacent growth-rings that had a zone of earlywood greater than or equal to 50% of their overall width. It was assumed that such growth-rings might have been formed during the shredding years. In contrast, the sequences up to 20 rings which occurred at the beginning of measurement series and were characterised by narrow earlywood zones may be suspected of coming from coppiced trees. In this case the limit was taken as the share of earlywood in the entire growth-ring width was less than 25%.

Since these adopted boundary values are not justified by the literature or previous studies, the results of earlywood calculations were considered as supplementary. Therefore, when these values coincided with the analysis of measurements of growth-ring width, the obtained result was an additional confirmation. However, if this correspondence was not observed, the result received was not treated as ruling out the existence of abrupt growth change.

Growth suppressions and releases in the growth ring sequences were preliminarily traced with the aid of the visual analysis of growth trends. The variability of growth-ring width, i.e., the presence of abrupt growth changes (reductions and recoveries), was specified also on the basis of calculations. For this purpose, a previously developed methodology [10,22] was used:

$$\mathrm{PGCr} = [(\mathrm{M}_2 - \mathrm{M}_1)/\mathrm{M}_1] \times 100$$

$$\mathrm{PGCs} = [(\mathrm{M}_1 - \mathrm{M}_2)/\mathrm{M}_2] \times 100$$

where PGCr and PGCs are the percentage growth change for releases and suppressions, respectively, and M_1 and M_2 are ring-width means of preceding and subsequent years (the number of years used to calculate the mean was adjusted for each sample). A change in growth was assumed to be present if the obtained value was equal or above 100%.

In addition, some dendrochronological statistics were calculated in order to analyse the variability of the growth-ring width in detail. For this purpose, the mean sensitivity and correlation coefficients were determined COFECHA program [31]. Mean sensitivity reflects the proportion of high-frequency variance in the sequence of tree-rings. Tree-ring series are considered to be sensitive when their ring-width varies markedly from year to year, and the mean sensitivity value is greater than 0.30. In turn, tree-ring sequences that have similar growth-ring width every year are called complacent, and their mean sensitivity is lower than 0.30 [32]. In turn, autocorrelation coefficient estimates the autoregressive structure and reflects the proportion of low-frequency variance in tree-rings. High autocorrelation value means that the width of the growth-ring is strongly influenced by the width of the ring formed during the previous years and is considerably affected by external conditions in the preceding years. High autocorrelation also indicate that low-frequency fluctuations have a substantial contribution to the width of growth-rings and suggests the existence of significant trends in tree-ring sequences [33].

3. Results

Altogether, 190 samples of wood from the Bruszczewo site were measured during this study. In the taxonomical composition, the oak wood dominated, with 120 samples belonging to this taxon. In addition to the oak, 30 alder, 14 ash, 13 elm, 9 maple and four specimens of pine (*Pinus* L.) were present (Figure 4). Among these wood samples, only pine is a gymnosperm genus and therefore reacts in a different way to the influence of external factors in comparison to the other, angiosperm species. Therefore, four samples classified as pine wood were excluded from further research. This decision also resulted from the fact that forest management systems discussed in this article are applied to broad-leaved trees. In addition, alder was also omitted because a specific type of growth characterises this taxon. Alder usually overgrows the wetland stands stretching along riverbanks and often located on unstable grounds. Such habitat is conducive to the frequent occurrence of reaction wood, the variable width of growth-rings, the lack of continuous growth at the entire circumference of the stem, and the existence of false rings. Therefore, these features should not be linked with the impact of forest management practices, but they instead result from natural variability of tree growth.

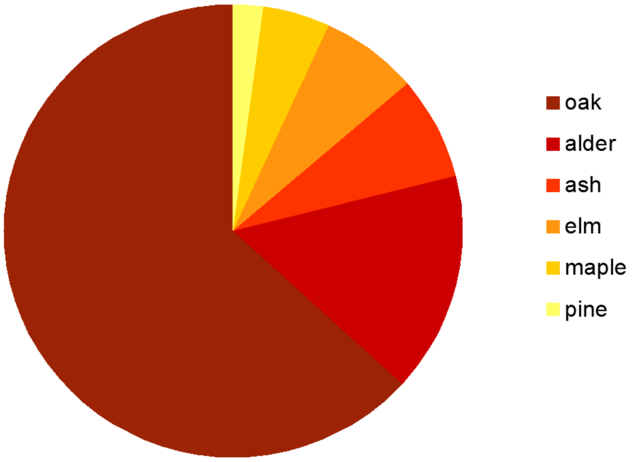

Figure 4. Percentage share of individual tree species within analysed samples.

The analysed wood was very diverse regarding the number and width of growth-rings. The average number of growth-rings within a single sample was 37.18. The total number of growth-rings varied from 13 to 107 within a particular sample, and among them, 32 samples had at least 50 growth-rings (Figure 5). In turn, 30 of the analysed samples did not have a preserved pith. However, on the basis of the curvature of growth-rings and the divergence of the medullary rays, it was established that for 8 of them the distance to the pith was very small and only a few innermost rings were missing. On the other hand, 51 samples were devoid of the external part of the trunk, with partially present or completely removed sapwood rings (in the case of sapwood species). The sapwood zone is most susceptible to wood decomposition process and therefore is usually preserved in a worse state than the heartwood rings. Nevertheless, the overwhelming majority of the analysed wood had the outermost ring (waney edge).

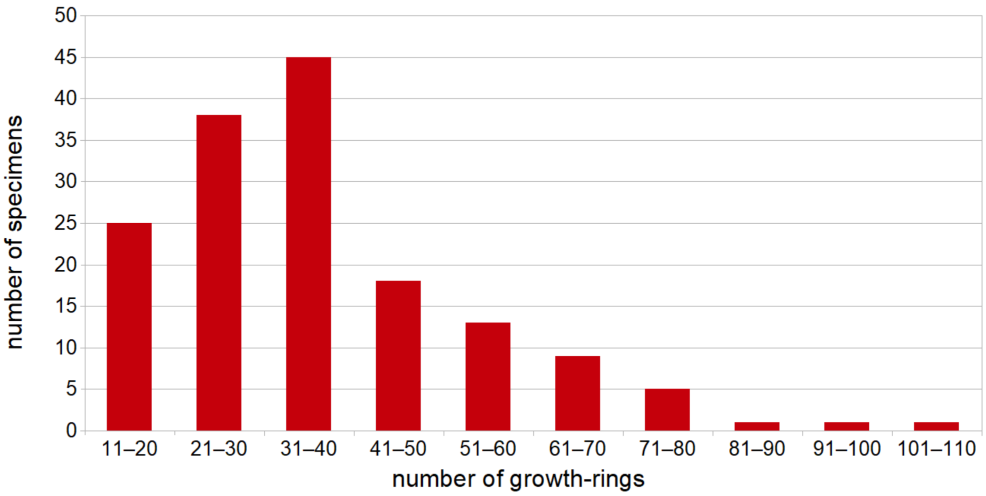

Figure 5. Distribution of tree age classes within analysed samples.

The features mentioned above indicate that most of the analysed wood derives from the trees that were very young at the felling time. Simultaneously, these samples are characterised by a fast growth rate and a large width of growth-rings. The average growth-ring width for the analysed wood varied from 0.43 mm to 5.33 mm for particular samples, and the mean growth-ring width was 1.53 mm for all samples, while it was bigger than 2 mm for 45 samples. The maximum growth-ring width was 7.95 mm (Table 1). The average ring width is supposed to provide information on many environmental factors, e.g., stand density, soil fertility, soil texture, water capacity and others. It is believed that the growth-ring width greater than 2 mm indicates very favourable environmental conditions and unlimited access to substrates used during the assimilation process.

The trees growing in the Bruszczewo area, despite their young age and the small number of tree-rings presented in their wood, reached significant thickness of stems because large width of these rings. This is particularly evident in the case of oak poles originating from the fascine constructions, which usually had less than 50 rings, and most frequently around 30 rings (Figure 5). These features prove that the trees were living on wet stand and their growth was never limited by water availability. Nevertheless, the special attention must be paid also to the fact that the analysed wood comes from young trees. Therefore, the large width of rings allows the conclusion to be drawn that the trees grew in a sunny place since the seedlings germinating in the closed canopy stands, during juvenile stage of development produce narrow rings as a result of the competition for light. This agrees with the conclusions of the pollen analysis indicating that the land at the time was quite open with single groups of trees in the landscape [5]. Young age and fast growth rate are distinctive for wood formed in coppiced stands.

Simultaneously, the analysed samples were characterised by a broad range of ring widths. The minimum measured growth-ring width was 0.07 mm, while the maximum was equal to 7.95 mm (Table 1). Such a high variability of growth-ring width is the result of abrupt growth changes frequently occurring in the studied wood. A measure of the relative variation in the ring-width from one year to the next one is mean sensitivity coefficient. In Bruszczewo wood, the mean sensitivity for individual samples varied from 0.13 to 0.62, with 92 samples being higher than or equal to 0.3, and the average value for all samples was 0.30 (Table 1). This proves that the analysed rings were sensitive and that they were affected by the changeable influence of external factors that limited the growth of trees during their lifetime.

Table 1. Characteristics of the samples from Bruszczewo site used during dendrochronological research.

Sample	Number of Rings	Outer-Most Ring Preset [p]	Number of Sapwood Rings	Pith Present [p]	Reaction Wood Present [p]	Double Pith Present [p]	Sapwood Percentage [%]	Mean Measurement	Maximum Measurement	Standard Deviation	Auto Correlation	Mean Sensitivity	Species	Forest Management Technique
Bru1	49	p	0	p	p			1.19	2.49	0.529	0.311	0.381	*Acer* sp.	shredding
Bru2	20		0	p	p	p		2.99	5.04	1.547	0.591	0.372	*Quercus* sp.	
Bru3	63		0	p	p			0.94	2.28	0.463	0.794	0.220	*Quercus* sp.	coppicing
Bru4	30	p	9	p	p		19.89	1.91	3.65	0.720	0.650	0.254	*Quercus* sp.	coppicing
Bru5	31	p	0	p				1.35	2.64	0.526	0.533	0.313	*Ulmus* sp.	coppicing
Bru6	38	p	17	p	p		23.21	1.12	3.28	0.732	0.848	0.253	*Quercus* sp.	coppicing
Bru7	50		0	p	p			1.09	2.06	0.344	0.478	0.231	*Quercus* sp.	
Bru8	19	p	0	p				2.19	5.22	1.525	0.674	0.615	*Acer* sp.	shredding
Bru9	14	p	7	p	p	p	46.53	1.90	3.77	1.048	0.545	0.330	*Quercus* sp.	coppicing
Bru10	41	p	13 plus 2 or 3	p	p		17.82	0.92	3.33	0.546	0.690	0.279	*Quercus* sp.	shredding
Bru11	30		0					2.40	4.27	0.798	0.634	0.181	*Fraxinus excelsior* L.	
Bru12	50		0					0.86	2.32	0.520	0.691	0.281	*Quercus* sp.	shredding
Bru13	25	p?	7	p	p		27.40	2.09	3.74	0.834	0.266	0.373	*Quercus* sp.	
Bru14	34	p?	0	p				1.37	3.12	0.752	0.567	0.393	*Alnus* sp.	
Bru15	32	p	0	p				0.91	1.74	0.471	0.812	0.249	*Ulmus* sp.	coppicing
Bru16	18		0					2.33	4.45	0.895	0.604	0.269	*Quercus* sp.	
Bru17	72		0					0.52	1.09	0.168	0.668	0.200	*Quercus* sp.	
Bru18	40		0	p				0.71	1.61	0.309	0.587	0.311	*Quercus* sp.	
Bru19	28		0					0.92	1.68	0.374	0.552	0.316	*Quercus* sp.	
Bru20	45		0	p				0.71	1.57	0.372	0.830	0.221	*Quercus* sp.	coppicing
Bru21	33	p	0	p	p			0.98	2.03	0.390	0.355	0.299	*Alnus* sp.	
Bru22	18	p	?	p	p			2.42	3.58	0.610	0.243	0.258	*Quercus* sp.	
Bru23	16	p	7	p	p		33.91	2.44	4.94	1.022	0.435	0.299	*Quercus* sp.	coppicing
Bru24	22	p?	12	p	p		35.37	1.72	3.49	0.800	0.704	0.230	*Quercus* sp.	coppicing
Bru25	14		0 plus 5	p	p			3.30	5.25	1.233	0.156	0.411	*Quercus* sp.	
Bru26	43		0					2.03	2.99	0.452	0.330	0.209	*Quercus* sp.	
Bru27	37	p?	12	p			28.73	1.46	3.24	0.680	0.728	0.239	*Quercus* sp.	shredding
Bru28	27		0	p				2.91	4.16	0.628	0.468	0.192	*Quercus* sp.	
Bru29	17	p?	6	p	p		21.49	1.71	3.24	0.810	0.480	0.335	*Quercus* sp.	coppicing

Table 1. *Cont.*

Sample	Number of Rings	Outer-Most Ring Preset [p]	Number of Sapwood Rings	Pith Present [p]	Reaction Wood Present [p]	Double Pith Present [p]	Sapwood Percentage [%]	Mean Measurement	Maximum Measurement	Standard Deviation	Auto Correlation	Mean Sensitivity	Species	Forest Management Technique
Bru30	37	p?	7	p	p		11.44	1.01	2.61	0.533	0.745	0.316	*Quercus* sp.	shredding
Bru31	13	p	7	p		p	54.80	2.58	4.28	1.112	−0.196	0.478	*Quercus* sp.	coppicing
Bru32	87	p	0	p		p		0.54	2.56	0.487	0.799	0.374	*Alnus* sp.	
Bru33	37	p	13	p			32.29	1.47	3.21	0.607	0.547	0.356	*Quercus* sp.	shredding
Bru34	37	p?	12	p	p		12.17	1.11	2.93	0.752	0.737	0.303	*Quercus* sp.	coppicing
Bru35	60	p?	0	p				0.81	2.14	0.519	0.704	0.354	*Ulmus* sp.	shredding
Bru36	57	p?	0	p	p			1.13	3.71	0.816	0.798	0.309	*Ulmus* sp.	shredding
Bru37	46		0	p	p			0.95	2.35	0.642	0.870	0.269	*Acer* sp.	
Bru38	48		0	p				0.62	1.31	0.257	0.449	0.296	*Quercus* sp.	shredding
Bru39	41	p?	10	p	p		30.90	1.46	2.96	0.547	0.362	0.332	*Quercus* sp.	shredding
Bru40	58		0	p				1.93	2.79	0.418	0.264	0.227	*Quercus* sp.	
Bru41	19	p	11	p			64.82	2.24	4.00	0.897	0.650	0.269	*Quercus* sp.	
Bru42	107		0					0.59	2.29	0.250	0.638	0.199	*Quercus* sp.	shredding
Bru43	45		0	p				1.72	2.61	0.480	0.541	0.216	*Alnus* sp.	
Bru44	24	p	0	p				1.27	3.07	0.683	0.477	0.319	*Alnus* sp.	
Bru45	67		0					0.76	1.89	0.446	0.850	0.242	*Quercus* sp.	coppicing
Bru46	25	p	0					3.06	6.01	1.328	0.877	0.178	*Alnus* sp.	
Bru47	27	p	9	p	p		45.60	2.24	5.40	1.155	0.638	0.376	*Quercus* sp.	shredding
Bru48	19	p	15	p			77.31	4.03	5.61	0.904	0.191	0.247	*Quercus* sp.	
Bru49	52		0	p	p			0.63	1.45	0.281	0.753	0.226	*Quercus* sp.	
Bru50	34		0					0.60	0.99	0.168	0.596	0.185	*Quercus* sp.	
Bru51	14	p?	0	p				1.79	2.42	0.419	0.529	0.191	*Alnus* sp.	
Bru52	20	p	0	p				0.80	1.67	0.337	0.495	0.333	*Fraxinus excelsior* L.	
Bru53	34	p?	0					1.33	3.55	1.089	0.883	0.313	*Acer* sp.	coppicing
Bru54	25	p?	0					0.86	1.54	0.337	0.583	0.309	*Alnus* sp.	
Bru55	48	p?	0					1.26	3.96	0.707	0.538	0.310	*Fraxinus excelsior* L.	
Bru56	37		0					0.91	1.40	0.210	0.661	0.158	*Quercus* sp.	
Bru57	25	p	0	p	p			1.25	2.45	0.574	0.317	0.450	*Alnus* sp.	
Bru58	30	p	0	p	p			1.23	1.96	0.396	0.099	0.337	*Alnus* sp.	

Table 1. *Cont.*

Sample	Number of Rings	Outer-Most Ring Preset [p]	Number of Sapwood Rings	Pith Present [p]	Reaction Wood Present [p]	Double Pith Present [p]	Sapwood Percentage [%]	Mean Measurement	Maximum Measurement	Standard Deviation	Auto Correlation	Mean Sensitivity	Species	Forest Management Technique
Bru59	65	p	0	p	p			0.56	1.06	0.258	0.734	0.265	*Fraxinus excelsior* L.	
Bru60	33	p	13	p			27.95	0.95	3.04	0.715	0.746	0.313	*Quercus* sp.	coppicing
Bru61	28		0	p				1.49	7.06	1.594	0.753	0.471	*Alnus* sp.	
Bru62	22	p	12	p		p	49.79	2.44	4.11	0.875	0.462	0.269	*Quercus* sp.	
Bru63	45	p	21	p	p		38.79	0.87	2.37	0.371	0.372	0.334	*Quercus* sp.	shredding
Bru64	13	p	5	p	p	p	34.79	3.31	5.79	1.253	0.038	0.437	*Quercus* sp.	
Bru65	23	p	5	p	p		27.00	2.88	4.71	1.040	0.604	0.244	*Quercus* sp.	shredding
Bru66	17		0					2.96	4.31	0.776	0.191	0.261	*Quercus* sp.	
Bru67	38	p?	13	p	p		13.53	1.13	2.23	0.613	0.886	0.223	*Quercus* sp.	coppicing
Bru68	80		0					1.18	1.82	0.277	0.496	0.188	*Quercus* sp.	
Bru69	31	p	10	p		p	29.30	1.32	3.26	0.709	0.313	0.504	*Quercus* sp.	
Bru70	33	p	12	p		p	22.45	1.00	2.68	0.639	0.722	0.295	*Quercus* sp.	shredding
Bru71	33	p	12	p			18.35	1.07	2.20	0.563	0.501	0.322	*Quercus* sp.	
Bru72	34	p	12	p			29.41	1.13	3.94	0.786	0.711	0.333	*Quercus* sp.	shredding
Bru73	76	p	0	p	p			0.59	1.77	0.312	0.501	0.370	*Alnus* sp.	
Bru74	15	p	0	p	p			3.81	6.51	1.545	0.698	0.240	*Pinus* sp.	
Bru75	28		0					2.22	3.37	0.460	0.308	0.181	*Quercus* sp.	
Bru76	27		0					1.45	2.54	0.469	0.130	0.328	*Pinus* sp.	
Bru77	39		0					1.99	3.10	0.372	0.303	0.184	*Quercus* sp.	
Bru78	34		0					1.03	2.06	0.452	0.860	0.180	*Pinus* sp.	
Bru79	23	p	0	p	p	p		1.59	3.37	0.800	0.547	0.411	*Ulmus* sp.	
Bru80	47		7	p			11.34	1.05	1.65	0.270	0.228	0.239	*Quercus* sp.	shredding
Bru81	22	p?	8 plus 1	p			32.87	1.69	3.42	0.550	0.444	0.224	*Quercus* sp.	
Bru82	26	p	12	p			35.25	1.70	4.00	0.952	0.444	0.348	*Quercus* sp.	shredding
Bru83	33	p	13				44.02	0.63	0.98	0.137	0.356	0.171	*Quercus* sp.	
Bru84	30		0					1.02	1.57	0.206	0.149	0.198	*Quercus* sp.	
Bru85	28	p	9	p	p		31.76	0.97	1.61	0.223	0.254	0.201	*Quercus* sp.	
Bru86	38	p	12 plus 1	p	p		44.79	0.86	1.77	0.436	0.645	0.387	*Quercus* sp.	shredding
Bru87	62		0	p				0.74	1.55	0.253	0.712	0.199	*Quercus* sp.	shredding
Bru88	21	p	0	p	p			1.97	4.57	1.194	0.211	0.542	*Alnus* sp.	

Table 1. *Cont.*

Sample	Number of Rings	Outer-Most Ring Preset [p]	Number of Sapwood Rings	Pith Present [p]	Reaction Wood Present [p]	Double Pith Present [p]	Sapwood Percentage [%]	Mean Measurement	Maximum Measurement	Standard Deviation	Auto Correlation	Mean Sensitivity	Species	Forest Management Technique
Bru89	35	p	8	p		p	12.10	1.40	2.99	0.719	0.844	0.186	*Quercus* sp.	coppicing
Bru90	80		0					1.37	4.61	0.915	0.489	0.454	*Alnus* sp.	
Bru91	19		0					3.78	7.89	1.901	0.320	0.531	*Alnus* sp.	
Bru92	36		0	p				1.40	2.60	0.466	0.338	0.336	*Alnus* sp.	
Bru93	31	p?	0	p		p		1.65	3.64	0.899	0.632	0.367	*Ulmus* sp.	
Bru94	43	p	12	p	p		27.38	1.00	3.01	0.487	0.297	0.407	*Quercus* sp.	shredding
Bru95	23		0					2.63	4.87	0.839	0.583	0.204	*Quercus* sp.	
Bru96	54	p	9	p	p		34.15	1.46	3.98	1.043	0.791	0.336	*Quercus* sp.	
Bru97	68		5	p	p		6.30	1.18	2.48	0.528	0.795	0.227	*Quercus* sp.	coppicing
Bru98	26	p	10	p		p	40.16	1.50	4.31	0.787	0.236	0.393	*Quercus* sp.	shredding
Bru99	20	p	10 plus 1 or 2	p			42.40	1.78	4.51	1.171	0.612	0.439	*Quercus* sp.	coppicing
Bru100	21	p	7	p	p		26.13	2.37	4.13	0.945	0.306	0.370	*Quercus* sp.	coppicing
Bru101	24	p	10 plus 1	p			39.30	1.32	3.01	0.644	0.309	0.414	*Quercus* sp.	shredding
Bru102	30	p	13	p	p		40.75	1.31	2.21	0.474	0.369	0.358	*Quercus* sp.	
Bru103	23	p	9	p			43.70	2.21	3.52	0.572	0.492	0.191	*Quercus* sp.	
Bru104	35	p	11	p	p		18.42	1.46	2.79	0.640	0.741	0.239	*Quercus* sp.	
Bru105	93	p	0	p	p			0.43	1.21	0.240	0.684	0.324	*Ulmus* sp.	shredding
Bru106	34		0	p				1.28	3.81	0.941	0.775	0.375	*Acer* sp.	coppicing
Bru107	59		0					0.75	1.62	0.336	0.396	0.386	*Alnus* sp.	
Bru108	19	p	0	p				1.94	4.34	0.982	0.286	0.433	*Fraxinus excelsior* L.	coppicing
Bru109	22	p	0	p				2.07	3.91	1.177	0.831	0.298	*Alnus* sp.	
Bru110	36	p	0	p				1.13	2.23	0.507	0.616	0.348	*Alnus* sp.	
Bru111	69	p	0	p				0.43	1.66	0.277	0.467	0.475	*Ulmus* sp.	shredding
Bru112	52	p?	0	p				0.72	1.76	0.375	0.403	0.436	*Alnus* sp.	
Bru113	36	p	15	p			58.90	1.15	4.12	1.000	0.680	0.438	*Quercus* sp.	shredding
Bru114	40		0					1.25	2.07	0.353	0.655	0.182	*Quercus* sp.	
Bru115	31	p	0					1.20	1.96	0.364	0.319	0.295	*Fraxinus excelsior* L.	
Bru116	63		0					1.03	1.46	0.177	0.497	0.128	*Quercus* sp.	
Bru117	22		0					3.21	5.25	1.185	0.509	0.314	*Quercus* sp.	

Table 1. *Cont.*

Sample	Number of Rings	Outer-Most Ring Preset [p]	Number of Sapwood Rings	Pith Present [p]	Reaction Wood Present [p]	Double Pith Present [p]	Sapwood Percentage [%]	Mean Measurement	Maximum Measurement	Standard Deviation	Auto Correlation	Mean Sensitivity	Species	Forest Management Technique
Bru118	35	p	20 plus 1 or 2	p			34.38	0.94	3.42	0.889	0.633	0.406	*Quercus* sp.	coppicing
Bru119	29	p?	6	p		p	47.83	1.99	7.84	1.760	0.744	0.409	*Quercus* sp.	coppicing
Bru120	28		0 plus 12	p				1.73	2.65	0.524	0.288	0.282	*Quercus* sp.	
Bru121	28	p	0	p	p			1.36	2.57	0.636	0.660	0.312	*Fraxinus excelsior* L.	coppicing
Bru122	30	p	0	p	p			1.96	3.24	0.638	0.443	0.271	*Fraxinus excelsior* L.	
Bru123	60	p	0	p	p			0.88	2.39	0.491	0.708	0.281	*Fraxinus excelsior* L.	shredding
Bru124	63	p?	0	p				1.00	5.12	0.847	0.336	0.496	*Alnus* sp.	
Bru125	66		0	p		p		1.81	2.96	0.500	0.506	0.205	*Quercus* sp.	
Bru126	23	p	10	p		p	48.35	2.12	3.40	0.554	0.452	0.186	*Quercus* sp.	
Bru127	35	p	15	p	p		30.97	1.35	2.94	0.617	0.766	0.227	*Quercus* sp.	
Bru128	36	p	11	p	p		17.21	1.30	3.64	0.793	0.706	0.276	*Quercus* sp.	coppicing
Bru129	33	p	12	p	p		36.84	1.07	3.83	0.586	0.199	0.279	*Quercus* sp.	coppicing
Bru130	32		0					2.11	3.21	0.616	0.329	0.262	*Fraxinus excelsior* L.	
Bru131	42	p?	0	p	p			0.66	1.36	0.295	0.583	0.362	*Alnus* sp.	
Bru132	36	p	17	p	p		52.99	0.97	2.65	0.503	0.102	0.410	*Quercus* sp.	
Bru133	15	p	6	p	p	p	38.34	2.81	5.41	1.261	0.390	0.354	*Quercus* sp.	
Bru134	24		0	p	p			3.87	5.95	1.128	0.175	0.331	*Quercus* sp.	
Bru135	16	p	7	p			47.04	3.23	4.90	0.934	0.427	0.235	*Quercus* sp.	
Bru136	23	p	0	p	p			1.44	2.68	0.779	0.674	0.434	*Acer* sp.	coppicing
Bru137	70	p?	0	p	p			0.75	2.60	0.534	0.675	0.395	*Alnus* sp.	
Bru138	21	p	0	p	p			2.22	5.32	1.432	0.594	0.534	*Ulmus* sp.	shredding
Bru139	28	p	0	p		p		1.24	2.39	0.398	0.132	0.275	*Ulmus* sp.	shredding
Bru140	32	p	0	p	p			1.48	3.80	0.927	0.339	0.466	*Fraxinus excelsior* L.	shredding
Bru141	26	p	10	p		p	32.13	2.08	4.51	0.786	0.553	0.232	*Quercus* sp.	
Bru142	51	p	11	p	p		15.77	0.97	2.37	0.590	0.689	0.317	*Quercus* sp.	coppicing
Bru143	29		0	p				0.90	1.58	0.348	0.599	0.273	*Alnus* sp.	
Bru144	74	p	2 plus 10	p	p		2.94	0.70	1.64	0.270	0.744	0.212	*Quercus* sp.	

Table 1. *Cont.*

Sample	Number of Rings	Outer-Most Ring Preset [p]	Number of Sapwood Rings	Pith Present [p]	Reaction Wood Present [p]	Double Pith Present [p]	Sapwood Percentage [%]	Mean Measurement	Maximum Measurement	Standard Deviation	Auto Correlation	Mean Sensitivity	Species	Forest Management Technique
Bru145	28		0					1.17	2.36	0.465	0.434	0.297	*Quercus* sp.	shredding
Bru146	35	p	21	p			31.47	0.87	2.96	0.733	0.809	0.320	*Quercus* sp.	coppicing
Bru147	56		0					0.60	1.91	0.394	0.248	0.533	*Quercus* sp.	shredding
Bru148	41	p?	4 plus ?	p			10.77	1.08	3.14	0.567	0.477	0.354	*Quercus* sp.	shredding
Bru149	27		0			p		1.39	2.44	0.524	0.357	0.287	*Quercus* sp.	
Bru150	33		0					0.74	1.80	0.366	0.675	0.285	*Alnus* sp.	
Bru151	37	p	21	p		p	49.31	0.66	2.07	0.347	0.232	0.364	*Quercus* sp.	shredding
Bru152	40	p	0	p				0.60	0.96	0.149	0.476	0.218	*Fraxinus excelsior* L.	
Bru153	17	p	0	p	p			1.79	3.55	0.832	0.600	0.286	*Fraxinus excelsior* L.	
Bru154	37	p	0	p	p			0.96	2.44	0.588	0.576	0.386	*Acer* sp.	shredding
Bru155	42		0					0.72	2.13	0.430	0.683	0.387	*Alnus* sp.	
Bru156	17	p	8	p	p		30.53	2.26	4.80	1.184	0.615	0.370	*Quercus* sp.	coppicing
Bru157	36	p	15 plus 1	p			26.88	1.78	4.07	0.877	0.474	0.329	*Quercus* sp.	
Bru158	25	p	9	p		p	29.96	2.47	4.29	0.838	0.599	0.248	*Quercus* sp.	
Bru159	31		0	p				1.49	2.23	0.389	0.406	0.248	*Quercus* sp.	
Bru160	40	p	15 or 16	p	p		27.84	1.37	3.05	0.553	0.556	0.300	*Quercus* sp.	
Bru161	33	p	16 plus 1	p	p		38.71	1.47	3.08	0.656	0.747	0.251	*Quercus* sp.	
Bru162	57	p?	0	p	p			0.93	3.20	0.796	0.700	0.405	*Acer* sp.	shredding
Bru163	21		0					2.80	3.50	0.322	−0.013	0.134	*Quercus* sp.	
Bru164	45		0	p	p			1.33	3.48	0.998	0.742	0.413	*Quercus* sp.	
Bru165	44	p	13 plus 1	p	p		14.44	1.16	2.51	0.615	0.524	0.326	*Quercus* sp.	
Bru166	47		1 plus 1	p		p	3.26	1.43	3.52	0.678	0.640	0.265	*Quercus* sp.	shredding
Bru167	56	p	22	p	p		18.45	1.01	3.95	0.740	0.689	0.321	*Quercus* sp.	coppicing
Bru168	78		0	p				0.76	1.84	0.435	0.835	0.245	*Quercus* sp.	
Bru169	64	p	1 plus ?	p			1.06	1.25	2.25	0.428	0.786	0.168	*Quercus* sp.	coppicing
Bru170	20		1?	p			4.80	4.37	7.00	1.601	0.321	0.382	*Quercus* sp.	
Bru171	83	p?	0	p	p			0.64	2.09	0.448	0.805	0.339	*Ulmus* sp.	shredding
Bru172	52	p	0	p	p			0.84	1.35	0.289	0.157	0.370	*Acer* sp.	
Bru173	35	p	0	p				1.19	2.90	0.720	0.773	0.313	*Alnus* sp.	

Table 1. *Cont.*

Sample	Number of Rings	Outer-Most Ring Preset [p]	Number of Sapwood Rings	Pith Present [p]	Reaction Wood Present [p]	Double Pith Present [p]	Sapwood Percentage [%]	Mean Measurement	Maximum Measurement	Standard Deviation	Auto Correlation	Mean Sensitivity	Species	Forest Management Technique
Bru174	12	p?	0	p	p			5.63	8.82	2.390	0.315	0.446	*Pinus* sp.	
Bru175	27	p?	0	p				1.68	3.10	0.608	0.380	0.300	*Alnus* sp.	
Bru176	18		0					5.33	7.95	1.531	0.684	0.189	*Fraxinus excelsior* L.	
Bru177	18		0					4.37	7.80	1.339	0.697	0.161	*Quercus* sp.	
Bru178	18		0	p				2.10	3.39	0.908	0.790	0.230	*Quercus* sp.	
Bru179	33	p	13	p		p	33.96	1.24	4.01	0.641	0.305	0.267	*Quercus* sp.	coppicing
Bru180	36	p	13	p			24.31	1.45	2.93	0.739	0.777	0.244	*Quercus* sp.	shredding
Bru181	46	p	14	p	p		19.58	1.15	2.73	0.486	0.602	0.245	*Quercus* sp.	
Bru182	51	p	0	p				0.78	2.29	0.561	0.790	0.345	*Ulmus* sp.	shredding
Bru183	25		0	p				2.17	3.85	0.816	0.442	0.336	*Quercus* sp.	
Bru184	22		0	p				3.57	5.29	0.942	−0.002	0.331	*Quercus* sp.	
Bru185	15	p	7	p	p	p	44.11	2.36	4.51	0.815	−0.085	0.393	*Quercus* sp.	
Bru186	32	p	12	p			40.64	1.28	2.04	0.439	0.183	0.351	*Quercus* sp.	shredding
Bru187	78		0	p				0.50	0.83	0.150	0.528	0.225	*Quercus* sp.	
Bru188	58	p	0	p				0.54	1.65	0.429	0.844	0.373	*Ulmus* sp.	shredding
Bru189	56		0					0.91	2.33	0.577	0.557	0.472	*Alnus* sp.	
Bru190	37	p?	0	p				1.18	4.43	0.874	0.570	0.399	*Alnus* sp.	

The symbol “?” means that the number of tree-rings could not be determined precisely.

The unstable environmental conditions also influence the values of autocorrelation. Autocorrelation values were relatively high in the analysed tree-ring series. The first order autocorrelation of individual samples varied from -0.12 to 0.88, with an average of 0.51 for all the samples, and with 105 samples having an average autocorrelation higher than or equal to 0.5 (Table 1). This points to the presence of short-term trends in the analysed growth-ring sequences. Relatively high values of mean sensitivity and autocorrelation coefficients can also confirm, in this particular case, the impact of strong, occasionally emerging external factors, such as coppicing or shredding practices.

The measurement of the growth-ring width allowed distinguishing two types of trees differing in the growth dynamics among the studied samples. The first of them was characterised by the occurrence of a sequence of wide growth-rings around the pith, covering the period of several to dozen or so years of the tree's initial lifespan. This zone of wide growth-rings was replaced in the next phase of the tree growth by a sharp decrease in the growth-ring width, lasting for several consecutive years (Figure 6). In this case, the reduction of the growth width was by 50% or more. Often, the growth suppression was the last stage of the tree's life which was followed by its cutting. A total of 34 measured samples were included in this type of growth. Among them, 28 were oaks, 2 ashes, 1 elm and 3 maples.

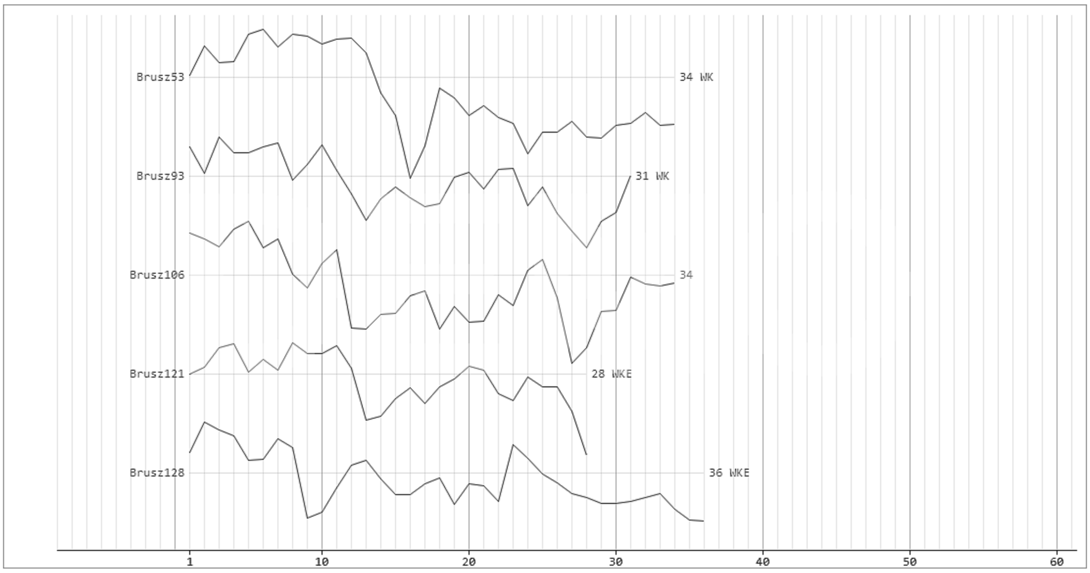

Figure 6. Examples of growth-ring sequences from coppiced trees.

The way of the earlywood development within particular growth-rings was another feature investigated in this wood. Performed study proved that the earlywood characterised by small, separated vessels, a diminished number of rows of vessels and decreased width, often occurred in these samples. Narrow earlywood zones with numerous and small vessels were visible in 31 analysed samples (21 oaks, 6 elms, 4 ashes). Usually, the earlywood possessed one or two rows of diminutive vessels, spaced apart from each other.

The second type of the growth, distinctly distinguished within the analysed samples, was the growth-ring pattern characterised by short zones of 3–4-year-long (up to 7 years) abrupt growth decline. Additionally, in this case, the drop in growth width was at least 50%. The occurrence of these zones within individual samples did not have a unified scheme. Sometimes, these reductions appeared at the beginning of a tree's life, but sometimes—in a later period. Usually, within a single wood, there were several suppressions zones (2–5), separated from each other by a time interval of several or dozen years (Figure 7). This type of growth was visible for 43 samples. Among them were 28 oak samples, 9 elms, 2 ashes and 4 maples.

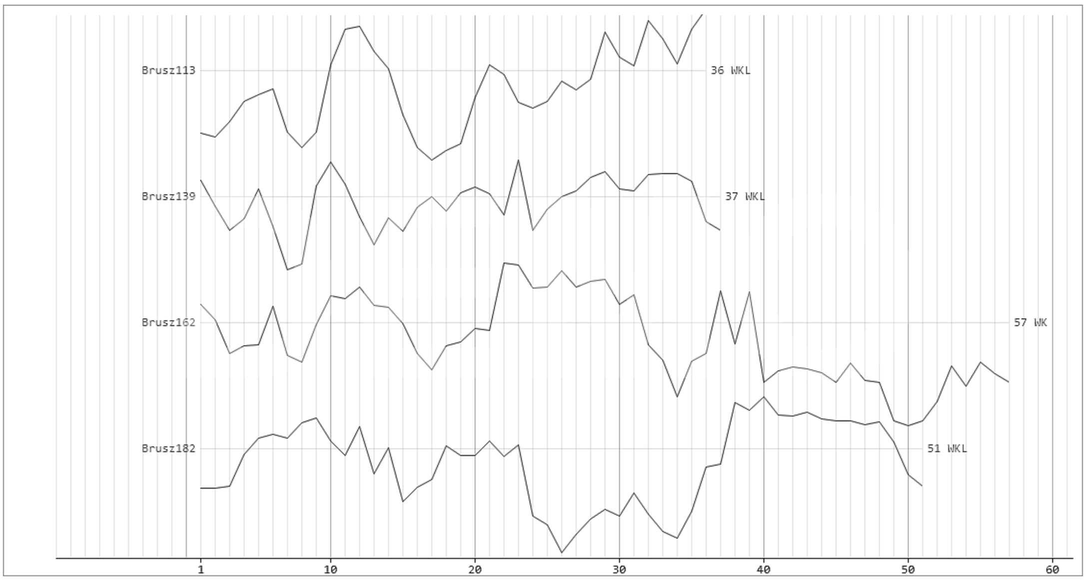

Figure 7. Examples of growth-ring sequences from shredded trees.

Simultaneously, most of these short-term reduction zones—30 samples—were marked by very wide earlywood in the year of shredding and then by a decline in the earlywood width in the 1–2 years following the shredding event. At the same time, the latewood of these zones was very narrow in the year of shredding and its width gradually increased in subsequent 1–3 years.

The sapwood zone of individual samples was also examined during the conducted research. As a result, it was established that 80 oak samples possessed sapwood rings and 75 of them were no more than 50 years old. Among them, 26 samples in the age class below 50 years had less than 10 sapwood rings. However, for five of these samples, the outermost ring was not observed because the outer part of the stem was removed or the external zone of the sapwood rings was deformed, and this fact precluded the recognition of the outermost ring (Table 1). Unfortunately, it cannot be exactly determined how many sapwood rings were absent. Nevertheless, sapwood zones of these samples were characterised by a large surface area in relation to the heartwood rings. For these trees, the sum of the sapwood rings width expressed as a percentage of the total width of all rings ranged from 11% to 55% in individual samples. At the same time, the percentage of sapwood area was strongly dependent also on the age of the tree and for older trees with a larger number of growth-rings this coefficient had lower values.

4. Discussion

Most of the analysed wood fragments from the Bruszczewo site possess specific growth-ring trends. All fluctuations occurring in growth-ring sequences result from numerous internal or external variables. The stand density and the availability of sunlight are among the strongest influencing factors, especially in the case of juvenile trees. Usually, trees that grow in open canopy stands are characterised by a wide growth-rings around the pith. Afterwards, the width of the growth-rings gradually decreases towards the bark. In turn, the trees growing in shady, closed canopy forest, form the narrow growth-rings in the first years of their lives. At a later time, when the tree height reaches the canopy layer, the width of the growth-rings gradually increases [32]. However, these gradual growth tendencies differ from the abrupt trends observed in Bruszczewo wood.

The changes in the growth-ring width in the wood samples from the Bruszczewo site are sudden. The development of rapid changes in the width of the growth-rings is related to the influence of an extreme environmental factors. For example, temperature or precipitation as well as drought or flood of low intensity could result in abrupt changes in tree growth. However, these changes usually persist in a short period [34]. It is not the case of Bruszczewo wood where the observed suppressions or releases in growth-rings are prolonged in time.

In contrast to this, a strong crown or root damage which arise as a result of extreme environmental events such as volcanic eruptions, earthquakes, mass movements, landslides, avalanches, windstorms, hurricanes, snowstorms, fires, intense floods and droughts or insect outbreaks, cause abrupt and prolonged growth decline which is followed by a gradual recovery of growth. It is somewhat similar to the growth-ring pattern observed in Bruszczewo wood. However, such factors usually are not cyclical and do not occur with a high frequency. Therefore, these extreme events manifest themselves in tree-ring series as sporadically happening, long-lasting, sharp growth reductions [35]. Bruszczewo wood is different because such suppressions are frequent and occur within wood non-equal in terms of age.

The change in the tree's social status could also be mentioned among the natural factors that induce abrupt and prolonged variations in the tree-ring width. Sudden growth release could be a result of the gap formation in the canopy of closed forest. The comparable growth-ring pattern is visible in some samples of Bruszczewo wood. Furthermore, vigorous initial growth followed by a pronounced reduction in ring width could be expected in the trees (re)colonising an abandoned arable land or establishing themselves after a clear cut [11]. However, in this situation, the pioneer taxa, such as *Salix* and *Betula*, are expected to dominate, and not the taxa such as *Quercus*, *Fraxinus* and *Ulmus* that are most abundant within Bruszczewo samples.

Taking into account all of the arguments mentioned above, the observed rapid changes in the growth-ring curves which occur (not simultaneously) for many trees are difficult to explain on the grounds of natural phenomena. For this reason, the cause of the abrupt growth reductions and releases in Bruszczewo wood is, most likely, human activity. The observed growth-ring development is, most probably, a consequence of silvicultural practices performed in the prehistoric forest. The analysis of the growth-rings structure points to coppicing and shredding as the techniques used in the case of the trees that overgrew the Bruszczewo stand.

Coppicing, pollarding (topping) and shredding are the silvicultural techniques that rely on the cyclic cutting of stems and branches of broad-leaved trees and shrubs [13]. These practices take advantage of the capacity of woody plants to sprout, after being cut, from the buds on the stumps or from root suckers. In hardwood stump, sprouts take birth both from dormant and adventitious buds [10,11]. Re-sprouting ability is determined by the formation, protection and resourcing of viable buds, after dramatic disturbance events such as flood, drought, fire, windstorm or human impact. Supplying buds development after the damage of the aboveground part of the plant requires the mobilisation of nutrient resources. This is achieved by the dislocation of carbohydrate reserves from the underground portions of the trunk and/or from the root system. The presence of belowground biomass and the potential of movement of the stored materials to basal buds can be considered as the main factors differentiating the life histories and growth strategies of sprouts from coppiced and from seeded trees in the same habitat conditions. Nevertheless, in a large number of angiosperms, re-sprouting ability after felling differs with the stage of tree development. For example, for sessile oak (*Quercus petraea* (Matt.) Liebl.) re-sprouting is possible but its probability decreases with stump diameter and age. Stems belonging to old, extensive root systems had a lower growth potential than those with smaller belowground biomass [19].

Coppicing consists of cutting trees close to the base of the trunk and letting them re-sprout from the cambium or dormant buds. In a coppiced forest, young tree stems are repeatedly cut down to near ground level. It is usually carried out during winter. In subsequent years many new shoots will emerge, and, after a number of years the coppiced tree, called stool, is ready to be harvested, and the cycle begins again [10,17,36].

In a simple coppice system, trees are grown as a single storey, equal in age crop and they are cut after a certain period, defined as a coppice cycle. The cycle length depends on the species, the local custom and the use to which the product is designed [17]. Coppice cycles usually vary from four to 25 or 30 years [19,20]. After the coppicing event, the remaining stools form new sprouts that replace the harvested poles [20]. In the case when some trees in coppiced woodland are allowed to grow bigger, this different silvicultural system is called coppice with standards. In this system, there are scattered individual stems that are named standards and treated as timber trees (they are frequently oaks). The long-lived standards, which usually are the trees of generative origin, form a scattered canopy over the short-rotation underwood. The standards grow through several rotations of the coppice cycle before they are harvested but the trees other than standards (the underwood) are felled every 5–25 years, and then they grow again [17,20]. Both of these forest management systems, coppice and coppice-with-standards, lead to the development of the specific growth ring pattern which was observed in Bruszczewo wood.

Coppiced trees, i.e., the trees regenerating from a stool, are specified by a vigorous initial growth which manifests itself in wide growth rings during the first cambial age class, especially during 1 to 10 years, starting from the pith [18]. The time span of this trend depends on the tree species and site conditions. Nevertheless, in the case of coppiced trees, the growth-ring width during the juvenile phase is clearly higher in comparison to the radial growth of dominant trees which germinated from seeds [11]. The vigorous initial growth of shoots from coppiced stools is the combined effect of the well-developed root system already present and the absence of light and nutrient competition which is a result of diminished number of individuals in the stand [11]. After the coppicing event, more solar radiation reaches not only tree crowns but also the surface of the soil. Therefore, the topsoil warms earlier in the spring, organic matter decays more rapidly and nutrients are more quickly released [37]. This is an additional factor which positively affects the supply of substrates for assimilation process. The raised light intensity and quality in early spring enhances soil microbial activity and mobilises soil nitrogen that can be utilised by trees to jump increase their radial growth. Another reason for the growth ring release could be the temporary reduction of the competition for water. Enhanced water availability could trigger the abnormal, elevated tree-ring growth following the coppicing event [10].

For the coppiced trees, the second stage of growth is also characteristic. When coppiced trees reach an age of about 20 years, their growth rate rapidly decreases and the initial phase of vigorous growth is, usually abruptly, followed by a substantial reduction (of about 50%) in the ring width. This is related to the moment where the individual shoots on a single stool become overgrown by each other or by shoots from neighbouring stools. Therefore, this growth reduction is connected with a rapid increase in concurrence between shoots in coppice stools as well as competition with other trees. The growth rate of coppiced trees tends to stabilise at the age of 50–60 years [11,19].

In the analysed wood from Bruszczewo site very wide growth rings around the pith were observed within 34 samples. All of these trees distinguished themselves by the zones of abrupt growth reduction occurring after a vigorous initial phase of growth. These trends observed in Bruszczewo wood coincide with the growth-ring pattern indicative for coppiced trees.

Other morphological and anatomical features can also distinguish coppiced and seeded trees. One specific aspect of the coppiced young wood is the large proportion of sapwood in the cross-section of the stem (the higher percentage of sapwood area) in comparison to old coppiced trees and seeded trees. The wood from the young coppiced trees thus yields a reduced amount of durable heartwood [18]. Simultaneously, a total number of sapwood rings is smaller in the case of young coppiced trees in comparison to old coppiced trees and normal trees. In the age class with the youngest trees, i.e., up to 50 years old, the number of sapwood rings in coppiced oaks is only 7 ± 2, while in seeded trees the standard is usually 16 ± 5 sapwood rings (in the area of Greater Poland about 13 sapwood rings). When the shoots are allowed to grow beyond 50 years, the number of sapwood rings in coppiced oaks rises to the standard estimate. For older trees, up to 200 years, the mean number of sapwood rings never differs more than six years from the standard value and falls within the range of the standard deviation [15]. The small number of sapwood rings in young coppiced trees and relatively large width of the sapwood zone indicate that the trees grew in favourable environmental conditions and within low competition stands [38].

A small number of sapwood rings and wide sapwood area were observed within 26 samples of Bruszczewo wood. In general, about one-third of the samples which possessed sapwood rings distinguished themselves by sapwood features that point to the origins from coppice stools. These samples had less than 10 sapwood rings (in the age class below 50 years). Moreover, the sapwood zones of these samples were characterised by a large surface in relation to heartwood rings. The percentage of sapwood area ranged from 11% to 55% in individual samples.

The earlywood zones of coppiced and seeded trees present significant differences in wood anatomy as well. Tree-rings from coppice shoots have smaller and more numerous earlywood vessels per unit area. Nevertheless, although the number of earlywood vessels per surface unit is higher in coppiced trees, the total surface proportion of the vessels is lower than that of seeded trees. As the effect, the earlywood width is greater in seeded trees [19]. The size of earlywood vessel area is mainly influenced by the cambial age but also results from the dimension of the tree, the position along the stem and the supply of water, carbon and nutrient substances during the formation of wood. These are the factors explaining the anatomical dissimilarities between coppice and seeded trees [19,22].

The described earlywood structure, typical for coppiced trees, was observed in Bruszczewo wood. Narrow earlywood zones with numerous and small vessels were visible in 31 of the analysed samples. Usually, the earlywood of these samples possessed one or two rows of small vessels, spaced apart from each other. These anatomical features confirm that the samples originated from coppiced trees.

The way of earlywood development affects water transport in coppiced trees. Coppice shoots have a lower total proportion of conducting tissue and, as a consequence, they possess lower hydraulic conductivity in comparison to seeded trees. It is because of the strong impact of large vessels in raw sap conduction, dominant in seeded trees [19]. These specific physiological conditions are the cause that coppice trees have a reduced height above the ground [18].

From the morphological point of view, coppiced stems are also characteristically curved at the base. This curve forms when the competing stems grow out from the stool in the early stage of the cycle, and later grow up when the canopy closes. The presence of such curves may allow the identification of coppice timber in archaeological sites [17]. However, in the case of Bruszczewo wood, the stem curvature at the base of tree was not observed. It results from the fact that the samples were preserved, in the vast majority, as small fragments of the logs.

Coppice management is also evident from the swollen collar zones and the straightness of the stems [12]. Sometimes, coppice stools create “stool heads”, which are swollen stem bases coming to existence through the vigorous development of callus, following the repeated cut back of coppice shoots. In ancient multi-stemmed trees, these massive bases result from the centuries of felling and regrowth [26]. However, similarly as in the case of stem curvature, it was difficult to detect the presence of this feature in Bruszczewo samples, due to the prevailing preservation of wood in the form of small fragments of trunks.

The short rotation systems, such as coppice and coppice-with-standards, also result in other specific stump characteristics. In dense groups of shoots, the cross-section of the stems is faintly oval; lengthwise there are very slight bends and only a small narrowing towards the top. Therefore, coppice management creates long straight poles which do not have the bends or bifurcations [17]. This shape is not seen in seeded trees [39].

Such morphological features as straight stems, low stumps and thickening or narrowing along the trunks were impossible to observe in Bruszczewo wood because of the fragmentary state of log preservation. However, oval cross sections were frequently noticed, especially in the case of young trees. The oval cross-section of the stem always coexisted with the reaction wood strongly developed on one side of the trunk. Reaction wood was clearly visible in 74 samples. Nevertheless, it is also important to remember that the formation of reaction wood does not have to be associated with coppiced trees only. The production of reaction wood is connected with any leaning of the stem from the vertical position.

Another stem peculiarity which relatively often occurred within the analysed samples, which is distinctive for coppiced trees, is the presence of double piths. The occurrence of two piths on the cross-section of the stem, surrounded by a partly individual and partly shared annual ring system, is the result of the production of two or more top shoots by the tree [34]. Therefore, double piths in the analysed wood indicate that the multiple stump sprouts were developed in the initial phase of tree growth. In turn, this multi-stemmed structure proves that the tree originated from a coppice stool [10,26]. The existence of double pith was observed within 25 of the analysed stem discs, i.e., in above 13% of the samples. It is a very high frequency which does not appear in natural tree stands.

In addition to wood from coppiced trees, among the samples from Bruszczewo site, some growth-ring sequences that correspond to standard trees could also be distinguished. The widely spaced tree standards originating from coppice-with-standards system follow the similar growth-ring tendency as the coppiced shoots. The standard trees also increase their radial growth after coppicing [20]. However, this growth release is smaller in comparison to the coppiced trees. The felling of underwood may result in faster growth of standard trees up to 20% [37]. The main factor inducing these abrupt growth changes in standard trees is the light level. Direct competition for light could have a significant effect, especially for young standards before they reach the canopy layer and are not shaded anymore [10]. The standard trees which have developed their full canopy are not strongly affected by the concurrence for light, but they are influenced, similar to as in the case of coppiced trees, by the diminished competition for soil nutrients and water resources after coppicing events [37]. The removal of neighbouring underwood enables young standards to grow beyond their usual increment. This effect gradually or abruptly declines as the re-sprouting underwood regains the space between standard trees [10]. A part of wood from Bruszczewo site is marked by the growth trend typical for young standard trees. These samples have wide zones of growth release, lasting until several decades, which are quite abruptly replaced by the prolonged zones of decreased growth. Nevertheless, there are no unambiguous criteria that would definitely classify wood for this type of growth. Coppice-with-standards management practice is not easy to confirm only on the basis of growth-ring measurements because a similar growth-ring tendencies can also result from the impact of other external factors.

The second silvicultural practice which was used in Bruszczewo forest is shredding. Shredding is one of three types of the pollarding management system. Pollarding refers to the removal of the top of a tree trunk or a tree crown as well as to the lopping of branches at a variable intensity and in a variable way [13]. In the case of shredding, both the tree trunk and the crown of a tree are kept intact, and only the side branches are cut off close to the trunk [16]. Shredding can be confused with trimming. However, trimming consists of cutting down all of the branches of a tree, from the bottom to the top. The term shredding is also close to pruning. To prune is to remove the branches from a tree but it is the word used for fruit trees only [13].

The removal of a large number of branches together with foliage, as in the case of the shredding practice, significantly reduces the leaf area index, and thus an overall plant assimilation rate as well as the biomass production and storage. Moreover, it restricts the accumulation of reserve carbohydrates that are used for early season growth. Due to diminished whole-tree photosynthesis, shredding suppresses the trunk enlargement and the root development [40]. As a result, the ring width of the shredded trees is affected by abrupt growth changes during the period of 3 to 4 years following the shredding event. Abrupt growth suppression of ring width appears during the first two years, and the gradual growth recovery occurs during the following years. The greatest reduction is seen in the year of shredding (reduction of about 46% of ring width) and the year subsequent to shredding event (reduction of about 50% of ring width). During the second year after shredding, the growth improvement is usually observed (regeneration of about 8%). After the second year, the effect of shredding on the ring width decreases [23,24]. Nevertheless, shredding carried out at close intervals prevent the tree from the growth increase. Moreover, in the case when trees were lopped regularly during a few years, and then shredding is abandoned, the regeneration is seen as a sharp rise in ring width after this prolonged time. After the cessation of shredding practice, an abrupt release is visible in the growth curve until the values equalling or exceeding those prior to the shredding event are reached [16]. The previous research has proved that leaf fodder was normally harvested from trees with an interval of 2–4 years, although trees could also be harvested every year. On the other hand, in some cases, there may be up to 7 or more years between cutting down the branches of each individual tree [16].

In the case of Bruszczewo wood, the influence of shredding practice was visible in many samples—43 of them had short-term reduction zones that can be associated with shredding impact. These samples were characterised by the occurrence of abrupt growth suppressions that often repeated several times within the growth-ring curve of one tree. These growth declines lasted for 3–4 years (up to 7 years) and were followed by a gradual recovery of the growth-ring width. However, it cannot be precluded that some part of these reduction zones was not associated with shredding practice because environmental factors could also cause a similar growth-ring pattern.

In order to better recognise the occurrence of shredding impact, it may be helpful to analyse the development of earlywood zone as well. The ratio between earlywood and latewood within the sequence of growth-rings from a shredded tree shows specific fluctuations. The earlywood width is not altered in the year of shredding. Therefore, the proportion of earlywood within the whole ring increases sharply due to the extremely low percentage of latewood in this year. Earlywood width in normal growth-rings usually constitutes 15–35% of a whole growth-ring. The percentage content of earlywood rises up to 90% within the ring formed during the shredding year. In turn, during the first and second years after the shredding event, the width of the earlywood is smallest. During these years, the width of latewood slightly enlarges in comparison to the year of shredding. After 3 to 4 years, the earlywood width progressively enhances at the same time as the latewood width [22,23]. Sometimes, heavy loss of crown or foliage can cause even a development of second earlywood during the year of shredding in ring-porous tree species [41].

In the case of Bruszczewo wood, the short-term reduction zones observed within individual samples were usually characterised by very narrow latewood in the year of shredding which increased gradually in subsequent years. At the same time these zones were distinguished by a stronger decline in the earlywood width in the years following the shredding event than in the year of shredding. The lack of decrease of earlywood width in the year of shredding results from the fact that the removing of branches intended for animal feed must take place after the beginning of the vegetation period, when the leaves are fully developed, and earlywood zone is already formed. Furthermore, deciduous trees, such as in the case of Bruszczewo plants, use for the production of earlywood a large extent the nutrient reserve materials originating from the previous year. Therefore, the impact of any extreme environmental conditions more significantly reflects itself in the diminishing of latewood width during the disturbance year. It is especially visible in the case of ring-porous trees, predominant in Bruszczewo samples, that always form growth-rings, no matter how unfavourable conditions affect the tree in a given year. During the growing seasons when the influence of limiting factors is extremely strong, the annual increment of these trees is almost exclusively composed of the earlywood [34]. Unfortunately, because different causes are responsible for the development of similar growth-ring structures therefore, it is difficult to distinguish shredded trees from all other trees that have been subjected to the action of various environmental factors limiting tree growth.

5. Conclusions

The analysed wood samples from Bruszczewo site were very variable, regarding the growth-ring number, growth-ring width and the way of individual growth-ring development. However, within these samples, it was possible to identify growth-ring patterns that indicate that the trees were subjected to the forest management practices during their life. A detailed study of the structure of growth-rings allowed distinguishing the samples originating from coppiced and shredded trees. A characteristic feature of the trees subjected to these silvicultural techniques is the presence of strong and abrupt suppressions or releases of growth, which sometimes appear several times within the individual sequence of growth-rings. Such zones of abrupt growth reductions and recoveries were frequently observed within the samples originating from Bruszczewo stand. In addition, the presence of some morphological and anatomical features confirmed the affiliation of the analysed wood into coppiced trees. These trees were characterised by the large proportion of sapwood in the cross-section of the stem, the small number of sapwood rings, small earlywood vessels, numerous earlywood vessels per unit area, low vessels total surface proportion within earlywood, as well as the oval cross-section of the stem and the presence of double piths. Furthermore, in the case of the shredded samples, the earlywood percentage within the whole growth-rings supported the theory about their origin from shredded trees. At the same time, all these changes observed in the wood structure, coming from coppicing and shredding signals in growth-rings, cause some problems during standard dendrochronological investigations and make difficult the cross-dating and the application of the tree-ring sequences into palaeoenvironmental research.

On the basis of measurements of growth-ring width, analysis of earlywood and latewood features, proportion of sapwood, very frequent presence of double piths and oval cross sections of the stems, it has been confirmed that coppicing and shredding techniques were already applied in Central Europe during the Early Bronze Age. Coppicing was used to increase the amount of harvested wood and to obtain wood with the relevant quality and properties. Shredding, on the other hand, made it possible to receive large quantities of leaves, which were utilised as fodder for domestic animals. The wood findings from the settlement of Bruszczewo, which are almost 4000 years old, provided a unique insight into prehistoric forestry, which must have been intensive and forward-planning given the wood requirements of the settlement and its fortifications.

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