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Dynamics of wood decay in the cross-section of logs as a result of long-term storage in a landing yard

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A study was carried out in three deadwood landing yards: two with pine wood and one with spruce wood. Three measuring baskets were placed on each landing yard. In each basket round timbers were arranged in three test layers. In each layer, seven round timbers were arranged. Two cross-sections were photographed on each roller. Photographs obtained during successive trials were analyzed with the MultiScan program. Measurements were taken 12 times, at the start (month 0) and then at intervals of 6, 9, 12, 15, 18, 24, 30, 36, 42, 48 and 54 months. It was found that blue stain became invisible on the cross-sections of pine round timbers after 12 months and in spruce after 6 months. On the cross-sections of pine round timbers, it was observed that hard rot appeared only after 9 months. In spruce wood, the presence of hard rot was already evident from month 0. In most cases, the largest areas of hard rot were found in the upper layers. In the case of soft rot, isolated cases of its occurrence were recorded only after 12 months in pine wood, and after 6 months in spruce wood. After 24 months the number of cross-sections with this type of rot increased sharply. Natural depreciation processes of wood raw materials resulting from long storage cause negative changes in its quality. However, these changes are not significant, meaning that after 54 months of storage, the wood is still mostly a full-value raw material.

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Introduction

In terms of structure and chemical composition, wood is a heterogeneous material, and questions of its changes and decomposition over time can be described separately, distinguishing such components as bark, phloem, cambium, sapwood or heartwood [Kokociński 2005]. Each component can also be considered chemically and anatomically. The differences that exist between earlywood and latewood, as well as differences in the structure of vessels and tubules affecting their diameters, affect the colonization potential of organisms involved in wood decomposition. Decomposition is also affected by the proportions of cellulose, hemicelluloses

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and lignin, the main building blocks of wood cell walls [Harmon et al. 1986]. Resins, gums and tannins can inhibit the access or development of wood-degrading agents, being toxic to bacteria, fungi and insects. Gums and resins also act as a mechanical barrier, making it difficult for organisms to access the anatomical and chemical components of wood that are attractive to them [Krajewski and Witomski 2016]. In addition to many factors directly related to the components of wood, the rate of decomposition is influenced by a number of other factors, such as climate (average annual temperature and precipitation), altitude, slope, exposure, micro-relief, type of surface (solid rock, bare or heavily vegetated soil, etc.), the fertility (nutrient availability) and moisture content of the habitat, the compactness, density and height of the stand, the position of the tree (standing, lying), the area of contact with the ground, the rapid fall of bark and drying of exposed wood, fungal infections before the tree dies, the cause of death (fire, wind, disease, insects, competition, age), and the presence of organisms involved in colonization and decomposition process in the environment [Naesset 1999; Zhou et al. 2007; Rock et al. 2008].

In the last century, Polish forests experienced numerous natural disasters, European spruce bark beetle gradations, and air pollution, which resulted in the appearance of large amounts of deadwood in a short period of time [Capecki 1969; 1993; Piszczek and Kuc 2013; Bruchwald et al. 2019]. In recent years, various disaster events have been observed, as well as prolonged periods of drought and declining groundwater levels, resulting in significant amounts of snags, even pine snags. Annually, this averages about 15% of the timber harvested in the National Forests [Statistics Poland 2023]. Such wood must often be stored in landing yards for long periods of time. This wood also tends to be of poor quality and is mostly used for fuel, less often for industrial purposes. The reason for this is the rapid appearance of blue stain and later decay. Even in the initial phase of decomposition, a significant decrease in bending strength has been reported, the changes being exponential [Witomski et al. 2016]. It was found that in the case of brown rot with a 7% weight loss and in the case of white rot with a 20% weight loss, the properties of the wood deteriorated by 50%. The presence of blue stain, especially decay, significantly limits the potential uses of the raw material, even as a medium-sized wood assortment. Hard rot is unacceptable in S1 (quarry, longwood), S2 (pulpwood) and S3 (poles) assortments. In contrast, soft rot is allowed only in the S4 (firewood) group, and only up to 50% of the end area. If the area of soft rot is greater, such wood is unusable and is treated as down woody debris [Kimbar 2011; Technical Conditions 2019a; 2019b].

The purpose of this study was to analyze changes in the magnitude of staining and decay occurring on the cross-sections of pine and spruce round timbers stored for a longer period of time in the landing yard. It was hypothesized that as a result of long-term storage of wood, the material would undergo significant decomposition. It should be emphasized that the research was carried out in landings where large amounts (several hundred cubic meters) of dead wood were collected and remained throughout the entire period of the experiment (54 months).

Materials and methods

Experimental landing yards for deadwood were established in three regions of central and southern Poland: in the area of the Regional Directorate of State Forests in Warsaw – the landing yard in Garwolin (denoted by the letter A) (pine wood, labeled as PI), in the area of the Regional Directorate of State Forests in Łódź – the landing yard in Spała (denoted by the letter B) (pine wood), and in the area of the Regional Directorate of State Forests in Wrocław – the landing yard in Lądek-Zdrój (denoted by the letter C) (spruce wood, labeled as SP) (Fig. 1). In each landing yard, about 600 m^3 of deadwood from trees that died in 2016 were deposited on rails (Fig. 1a) [Michalec et al. 2024].

At the stage of log pile formation, measurement points, called measurement baskets (Fig. 1b), were established in the form of rectangular structures, made of steel pipes, with a width of 1.2 m, a length of 2.5 m and a maximum height equal to the height of the log pile.

Fig. 1. Location of the experimental landing yards; a – landing yard in Spała; b – measurement basket

Fig. 2. Method of measuring the surface area of blue stain with the MultiScan program (photo taken during month 0) (photo by Wojciech Pasiowiec)

The interior of the measurement baskets was filled with straight round timbers with no visible curvature, which facilitated measurements and reduced the risk of error. In each log pile, three measurement baskets were set about 50 m apart to capture the widest possible range of external factors that could affect the stored wood.

In each measurement basket, 21 test round timbers were placed, representing the range of diameters of round timbers deposited in the log piles. The round timbers were arranged in three layers, i.e. the second from the bottom (referred to as bottom (1)), in the middle of the log pile height (called middle (2)), and the second from the top (called top (3)). Seven round timbers were laid in each layer. Immediately after the log piles were formed and the measurement baskets were filled with wood, the first measurements were taken. This was done in January 2017 (month 0). During formation of the log piles (month 0), both cross-sections on each measuring round timber were permanently marked with their respective code plates. Each end was then photographed (Fig. 2). The photos were taken using a Canon EOS 760D camera, always from a distance of about 1 meter, at the same angle, with a resolution of 72 dpi. During the photography, a grid of 1 cm squares was applied to each end. This was necessary for calibration of the MultiScan program, which was used for graphical analysis of the image (MultiScan v.18.03, Computer Scanning System, Poland). The program measures the size of the surface based on the color difference. This can be done automatically by setting the appropriate color scale, or manually. In these tests, in order to obtain accurate measurements, the shape of the colored areas (wood defects) was determined manually. Each end of the round timbers was photographed in each successive measurement trial. Photographs taken during month 0 were processed in the MultiScan program by measuring the area of the entire end (a and b), the area of blue stain (Fig. 2) or other staining, and hard and soft rot.

In subsequent measurements, the whole cross-sectional area was not measured, as it was unchanged from measurement 0. Using the measurements obtained, the following were then calculated: the percentage ratio of blue stain area to the area of the whole ends, and the percentage ratio of (hard and soft) rot to the area of the whole ends. To distinguish hard from soft rot, each end of the wood was cut with a special knife and the degree of decay was determined. If the wood chip had not decayed, it was treated as hard rot; if the wood had decayed, it was treated as soft rot.

The measurement procedure described above was carried out at the landing yards 12 times: immediately after the log piles were formed and the measurement baskets were filled with wood (month 0), and then at intervals of 6 months, 9 months and then 12, 15, 18, 24, 30, 36, 42, 48 and 54 months from month 0.

Because the null hypothesis of normality of the data distribution was rejected after applying the Shapiro–Wilk test, the Kruskal–Wallis test and the post hoc multiple comparisons test were used to analyze the statistical significance of the differences. Due to the large number of measurements, statistical analyses of the data collected after 54 months (at the end of the study) are included in the Results and Discussion section. Statistica 13.3 [Kot et al. 2007; Tibco Software Inc. 2017] was used for statistical analyses. The statistical analyses assumed a significance level of $p = 0.05$.

Results and discussion

1. Blue stain

Analyzing the proportion of blue stain area on the cross-sections of pine round timbers in the lower and middle layers (PI1 and PI2), a gradual decrease in blue stain area was observed over time (Fig. 3). Only

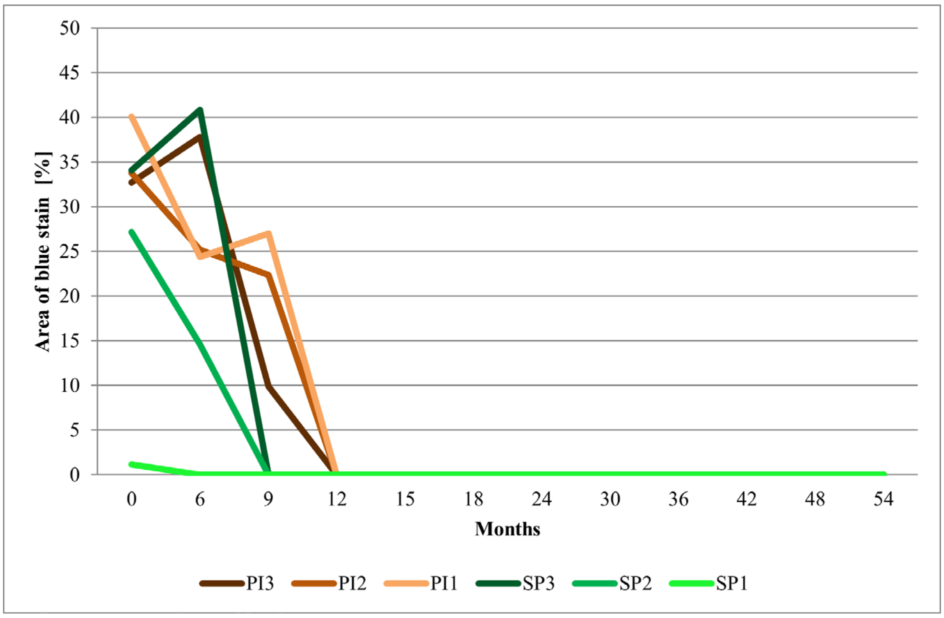

Fig. 3. Changes in the area of blue stain on the cross-sections of round timbers throughout the study period (PI – pine, SP – spruce; 1, 2, 3 – layers)

in the lower layer (PI1) was an increase in the area of cross-sections affected by blue stain observed after 6 months. This was associated with the spring–summer period, when climatic conditions were favorable for fungal growth. After this period, the area of blue stain decreased. On the other hand, round timbers in the top layer (PI3) showed an initial increase in the area affected by blue stain, and after 6 months the area decreased. After 12 months, blue stain was found to have disappeared on all the cross-sections tested. This was a result of the severe overdrying of the wood, the washing of the pigment from the mycelial hyphae by precipitation, and the developing hard rot, which began to replace the blue stain.

Similar trends were observed on spruce wood as on pine wood, with the disappearance of blue stain occurring more rapidly. In this case, blue stain disappeared on round timbers in the bottom layer (SP1) after just 6 months, and in the remaining layers (SP2 and SP3) after 9 months. The decrease in the area of blue stain was caused in this case by the rapid development of hard rot and the replacement of the area of blue stain by rot. The presence of hard rot on some cross-sections of spruce round timbers was already noted in month 0. According to Krajewski and Witomski [2016], blue stain can appear on wood immediately after it is cut. On the other hand, if the wood becomes overdried, hidden blue stain is formed and the staining may not occur. However, after the onset of unfavorable conditions, such as moisture in the wood, the discoloration may reappear. Szewczyk et al. [2020] found that the development of blue stain depended on both the duration of storage and the air temperature near the pile of pine wood. In particular, an increase in blue stain development was observed at temperatures above 16 °C, while blue stain development slowed down below 12 °C. The authors also found that the development and size of blue stain was more intense on wood harvested in summer than on wood harvested in spring. During our study, blue stain development was also found to be faster in summer (the period between month 6 and month 9), and decreased during the winter months. Unfortunately, the cited authors [Szewczyk et al. 2020] conducted their study for only 12 weeks; however, they found a steady increase in the area of blue stain. In our study, the period was much longer and the time interval between measurements was much larger (3 months). Consequently, a decrease in the area of blue stain was observed during wood storage. The effect of temperature, humidity and storage period was also determined by Millers et al. [2017]. In addition, they showed that the rate of development of blue stain is influenced by the way the wood is harvested (by chainsaw or harvester), the way the fungal spores are spread (by air movement or by insects), the location of the round timbers in the pile, the diameter of the round timbers, and the distance from the end. The rate of blue stain development and size can also be affected by tree species. Beal et al. [2010] found that when the wood was stored for 4 months, common pine exhibited the largest area of discoloration (about 70% of the area of the tested slice), and common spruce the smallest (about 10%). This may be due to the fact that pine wood showed the least change in moisture content during the 4-month experiment, and the final moisture content remained higher than that of spruce wood. In our study, smaller areas of blue stain can also be observed on spruce round timbers than on pine round timbers (Fig. 3). This is particularly evident on the round timbers in the lower (SP1) and middle (SP2) layers of the log pile.

2. Hard rot

In pine wood landing yards, hard rot appeared in all layers only after 9 months of storage of the raw material (Fig. 4). In most of the analyzed cases, the largest areas of hard rot were found in the top layer (PI3). On some round timbers, even at that stage, the area of decay reached up to 100% of the area of the cross-sections. Analyzing the rate of hard rot on the cross-sections, it can be concluded that the rate was slow in winter (the periods between months 9 and 15, 18 and 24, and 30 and 36), while it increased rapidly in spring and summer (the periods between months 6 and 9, 15 and 18, and 24 and 30). In the upper layer (PI3) after 36 months, and in the lower and middle layers (PI1 and PI2) after 48 months, a decrease in the area of hard rot was noted. However, this was due to the transition from hard rot to soft rot. Thus, the overall area of decay did not change, but the type of decay did.

In the case of spruce wood, in the bottom layer (SP1) the presence of hard rot was already noted on the

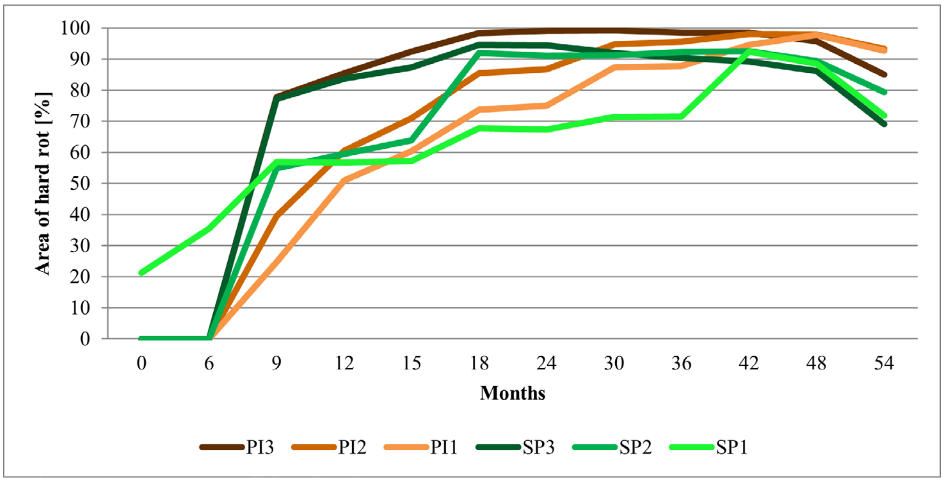

Fig. 4. Changes in the area of hard rot on the cross-sections of round timbers throughout the study period

Table 1. Statistical characteristics of rot identified on the cross-sections of round timbers after 54 months

Layer	Decay	Average [%]	Median [%]	Min [%]	Max [%]	Standard deviation [%]	Coefficient of variation [%]
PI3	hard	84.97	100.00	0.00	100.00	25.12	29.57
	soft	15.03	0.00	0.00	100.00	25.12	167.21
PI2	hard	93.31	100.00	0.00	100.00	18.90	20.25
	soft	6.69	0.00	0.00	100.00	18.90	282.26
PI1	hard	92.63	100.00	0.00	100.00	17.94	19.37
	soft	7.37	0.00	0.00	100.00	17.94	243.39
SP3	hard	69.08	100.00	12.81	100.00	23.92	28.45
	soft	25.92	12.16	0.00	100.00	23.92	150.22
SP2	hard	79.34	89.51	0.00	100.00	25.04	31.56
	soft	20.66	10.49	0.00	100.00	25.04	121.23
SP1	hard	71.80	80.49	0.00	100.00	33.20	46.24
	soft	28.20	19.51	0.00	100.00	33.20	117.74

Legend: PI – pine, SP – spruce; 1, 2, 3 – layers cross-sections at the start of the experiment (month 0). In the other layers (SP2 and SP3), hard rot appeared only after 9 months.

A sharp increase in the area affected by hard rot was observed in the top layer (SP3). In the other layers (SP1 and SP2), the increase in hard rot area was mild. After 18 months, in the upper and middle layers (SP3 and SP2), a decrease in the area of hard rot was observed. In the lower layer (SP1), such a tendency was found only after 42 months. The reason for this was the appearance of soft rot. Despite this, at the end of the study, after 54 months of storage of spruce wood (as in the case of pine), round timbers with cross-sections without hard rot were found, as well as round timbers with cross-sections completely (100%) covered by such decay (Table 1). The cross-sections of the analyzed round timbers (both pine and spruce) showed mainly gray decay [Krajewski and Witomski 2016]. This is a type of decay that occurs on wood in environments with frequent, large changes in moisture content. It progresses much more slowly in coniferous species than in deciduous species, and the extent of decay is minimal compared with that of white or brown decay.

3. Soft rot

At months 0, 6 and 9, no soft rot was observed in the pine wood. Only after 12 months were isolated cases of this type of decay recorded (Fig. 5). After 24 months, the situation of the round timbers in the lower and middle layers (PI1 and PI2) remained similar, and the increase in the area of soft rot was mild. Only on the cross-sections of the round timbers in the upper layer (PI3), after 24 months, was there a sharp increase in the area of soft rot. After 54 months of storage, the average area of soft rot on the round timbers in this layer was about 15%, with the presence of round timbers without soft rot on the ends, as well as round timbers with cross-sections completely (100%) covered by soft rot (Table 1).

In spruce wood, in turn, soft rot was found on the round timbers in the bottom layer (SP1) after only 6 months (Fig. 5). After 9 months, the presence of round timbers with soft rot was recorded in all layers. Up to the 24th month, the development of soft rot was slow, while between the 24th and 30th months of wood storage the rate of decay increased in the round timbers in all layers. After this period, the rate of soft rot development decreased. At the end of the study, after 54 months of wood storage, the average area of soft rot on the cross-sections of round timbers in the lower (SP1) and upper (SP3) layers was about 25%; as in the case of pine, there were some round timbers without soft rot on the ends, as well as some with cross-sections completely (100%) covered by soft rot (Table 1).

The Kruskal–Wallis test showed significant differences in the areas of decay on the cross-sections of the round timbers between different layers after 54 months ($H=41.929$; $p=0.000$). However, extending this analysis with a post hoc test, it was found that only the pine round timbers from the bottom (PI1) and middle (PI2) layers differed significantly from the spruce round timbers from all layers (Table 2). The round timbers from the other layers do not differ significantly.

Currently, the greatest amount of available knowledge relates to the decomposition rate of spruce wood. In southeastern Norway, the decomposition time of dead spruce trees under local conditions was found to be about 90 years. It was also noted that wood diameter, ground contact area, soil moisture content, and exposure had a significant effect on the rate of decomposition [Naesset 1999]. Other studies conducted in Norway found that decomposition of pine and spruce wood occurs after 60–80 years [Marikinen

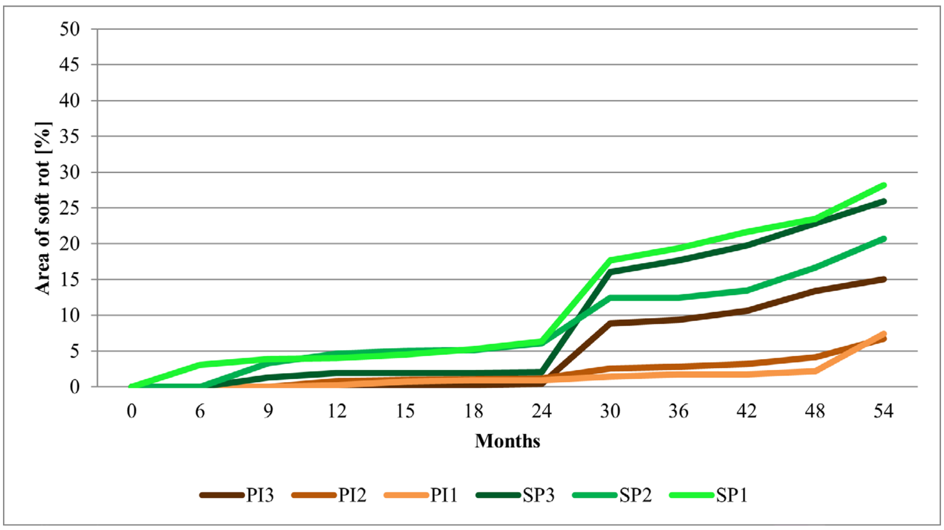

Fig. 5. Changes in the area of soft rot on the cross-sections of round timbers throughout the study period

Table 2. Results of post hoc test for rot located on the cross-sections of round timbers after 54 months

Layer	PI3	PI2	PI1	PI3	PI2	PI1
PI3	-	0.4380	1.0000	1.0000	1.0000	0.1264
PI2	0.4380	-	1.0000	0.0003	0.0115	0.0002
PI1	1.0000	1.0000	-	0.0004	0.0393	0.0007
SP3	1.0000	0.0003	0.0004	-	1.0000	1.0000
SP2	1.0000	0.0115	0.0393	1.0000	-	1.0000
SP1	0.1264	0.0002	0.0007	1.0000	1.0000	-

et al. 2006]. Under the conditions of the upper subalpine forest of the Polish Tatra Mountains and Babia Góra, the average minimum decomposition time was established at 70–80 years [Zielonka 2006]. In other studies, also conducted in the Tatra Mountains, the time to reach the highest degree of decomposition was a minimum of 60 years [Zielonka and Niklasson 2001]. On Babia Góra, it was determined that spruce debris could continue to decompose for about 160 years after the trees had died [Holeksa 1998]. The average decomposition time of dead spruce trees reported for Babia Góra depended on the diameter of the piece of wood; it was 71 years for logs less than 23 cm in diameter, 90 years for logs 23–35 cm in diameter, and 113 years for diameters greater than 35 cm [Holeksa et al. 2008]. The main reason for the slow decomposition of wood is low moisture content, which slows the growth of wood-degrading fungi. The present study also found faster wood decay in layers where precipitation had easier access to the wood of the upper layer (SP3). In turn, the wood of the lower layer (SP1) was more easily accessed by moisture from the ground. In the middle layer, decomposition was very slow.

Conclusions

1. The disappearance of blue stain on the cross-sections of pine round timbers after 12 months was probably due to the severe overdrying of the wood, the washing of pigment from the mycelial hyphae by precipitation, and the evolving hard rot, which began to replace blue stain.
2. After only 6 months of storage, hard rot began to appear in a wide range on spruce wood, much faster than on pine wood, taking the place of the more rapidly disappearing blue stain.
3. Analyzing the presence of hard rot on the cross-sections of pine wood, it was observed that hard rot appeared only after 9 months of storage of the raw material. The presence of hard rot in spruce wood, found already at the beginning of the experiment (month 0), may have been the reason that after only one-and-a-half years of storage (month 18), complete decay coverage was noted on the cross-sections of some round timbers. On the other hand, the change in the type of decay, i.e. the transformation from hard rot to soft rot, began after just two years (from month 24) of storage of the raw material in log piles.
4. Easier penetration of precipitation into round timbers located in the upper layers of the log piles (PI3, SP3) may have been responsible for the largest areas of hard rot found in the present study.
5. In the case of soft rot on pine wood, single cases of soft rot were reported only after 12 months. After 24 months, only on the cross-sections of the rollers in the upper layer (PI3) was there a sharp increase in the area of soft rot.
6. A faster increase in the area of soft rot on the cross-sections of spruce round timbers, compared with pine round timbers, was observed in all three layers (SP1–SP3) after just six months of storage, and it accelerated sharply two years after the log pile was laid. The presence of hard rot in some round timbers already at the time the log pile was laid may have been a factor in the more intensive decay of spruce round timbers.
7. Natural depreciation processes of wood raw materials due to long storage cause negative changes in its quality. However, these changes are not significant, meaning that after 54 months of storage, the wood is still mostly a full-value raw material.

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