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ORIGINAL PAPER

The analysis of the dynamics of changes in bark losses on the side surface of dead wood as a result of long-term storage in timber landings

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ABSTRACT

The goal of the present study was to analyse changes in bark losses on the side surface of dead wood left in the landing for a prolonged period of time. Three deadwood landings were established – two of these serving for the storage of pine timber, and one for spruce timber. Approximately 600 m^3 of deadwood was stored in each of the landings. At the stage of forming the log piles, measuring stations were established, called the measuring baskets, in the form of rectangular structures made of pipes, 1.2 metres wide, 2.5 metres deep and with a maximum height equal to the height of the log pile. The measuring baskets were located in the middle sections of the width of the log pile. At each landing, there were three measuring baskets with dead wood from local forests.

In each measuring basket which consisted of about 20 layers, the measured logs were arranged in three layers, specifically: in the second layer from the bottom, in the middle of the stack height, and in the second layer from the top. They were permanently marked, and designated as the 'test logs' F. In each layer, 7 logs were selected, representing the range of diameters of the logs assembled in the log pile. A total of 21 test logs were placed in each basket. Immediately after forming the stacks and filling the measuring baskets with timber, the first fieldwork was conducted and the following measurements were taken on site: the length of the test logs; the diameter with the bark in the middle of the log's length; also, on the side of the logs, the widths and lengths of traces of cut branches and the resulting damage to the bark. All measurement procedures listed above were carried out in the landings 9 times, that is: immediately after forming the stacks and filling the measuring baskets with timber (trial 0), and then at the following intervals: 6, 9, 12, 15, 18, 24, 30, 36 months after the zero trial. As a result of the analyses, it was determined that the logs located in the upper layer showed the greatest bark losses (by about 20-30% higher than other layers). During field research, it was observed that precipitation penetrated the upper layers of wood in the log pile more easily, which caused cyclical changes in bark moisture and, as a result, the bark fell off much more easily. The rainfall did not penetrate the lower layers, which made the logs dry out much more and the bark adhered more strongly to the logs side surface. In all landings, bark fell off at a similar rate (by approximately 10% every 6 months), and after 36 months of storing the wood, the share of bark

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on the logs was similar (about 30%), both on pine and spruce timber. Among the tested timber logs, both in trial 0 and in trial 8, there were logs completely devoid of bark (about 40%), and logs completely covered with bark (about 5%).

KEY WORDS

biomass, fuel-wood, medium-sized wood, pine, spruce, stripped bark

Introduction

The term 'bark' refers to all primary and secondary tissues located in the cross-section of the plant outside the pulp (outside the cambium) (Grochowski, 1990; Antkowiak, 1997) or 'the outer protective covering of the stem and branches of a tree' (EN 844:2019). The share of bark in the total weight of the trunk varies depending on the tree species. For Scots pine *Pinus sylvestris* L., it typically falls within the range of 10-17%, and for Norway spruce *Picea abies* (L.) H.Karst., it is in the range of 5-15% (Prosiński, 1984) – this means that the average share of bark for pine is 8.0%, and for spruce, it is 8.5% (PKN, 2002). The thickness of the bark, and therefore also its volume, depends on many factors. This is determined by the age of the trees and the fertility of the habitat (Stängle *et al.*, 2017; Dołkin *et al.*, 2018), as well as the diameter at breast height, the height of the trees, and their taper (Laasasenaho *et al.*, 2005; Božić *et al.*, 2007; Sonmez *et al.*, 2007). Nevertheless, we need to remember that the volume of bark is not included in the volume of wood, and that before wood processing the bark is removed and treated as waste. However, it can be used, among others, as fuel-wood (Jeżowski, 2003; Doruska *et al.*, 2009). The calorific value of completely dry bark is often close to the calorific value of wood itself (Prosiński, 1984; Jeżowski, 2003; Ferens, 2015). Unfortunately, the disadvantage of using waste bark as fuel-wood is its high humidity, which significantly reduces its calorific value, sometimes by as much as 50%. Another disadvantage of bark is its high ash content, which is, on average, *ca.* 2.14% (Antkowiak, 1997), and for coniferous trees even as much as 3.9% of the dry fuel mass (Gawlicki *et al.*, 2018). Some authors (Miranda *et al.*, 2012) report bark ash content of 3.3% for spruce and up to as much as 4.6% for pine.

In recent years, we have been witnessing various natural disaster events (hurricanes, droughts) that result in the emergence of large amounts of post-disaster wood. Also recently, we have observed significant amounts of deadwood – even pine deadwood – resulting from frequent periods of drought and the lowering of groundwater levels. Annually, this is, on average, about 15% of wood harvested in the State Forests (Statistics Poland, 2022). Such wood sometimes has to be stored in timber landings for lengthy periods of time. Often, that wood is also of poor quality, and therefore it is designated for fuel purposes. In such cases, the bark is an 'added value' that is not included in the wood volume.

Therefore, in the present study, an analysis was carried out to determine the changes in bark losses on the side of dead wood that remains in the landing for a prolonged time period. At the beginning of the research, it was assumed that the surfaces of the logs covered with bark would decrease.

Material and methods

Three deadwood landings were established – two of these serving for the storage of pine timber, and one for spruce timber (Fig. 1). Approximately 600 m^3 of deadwood was stored in each of the landings.

At the stage of forming the log piles, measuring points, called measuring baskets, were established in the form of rectangular piped structures; 1.2 m wide, 2.5 m deep, and with a maximum height equal to the height of the log piles (Fig. 2). The measuring baskets were located in the middle sections of the width of the log pile. The log piles at the timber landing were arranged in a way that allowed measuring baskets to be placed inside them, at a distance of not less than 50 m from each other, in order to capture the widest possible range of external factors that might affect the logged wood. Due to the assumed purpose of the present study, the wood in the measuring baskets and the wood adjacent to the baskets (at a distance of not less than 10 m on both sides of the basket, measured along the upper plane of the stack) was not otherwise utilised for the duration of the experiment (*i.e.* for 36 months).

The internal space of the measuring basket was filled with straight timber, without visible curvature, which made measurements easier and reduced the risk of calculation errors. At each depot there were three measuring baskets with dead wood from the area of local forests.

In each measuring basket, the logs were arranged in three layers, *i.e.* the second layer from the bottom [hereinafter referred to as the lower layer (1)]; in the middle of the stack height [hereinafter referred to as the middle layer (2)]; and the second layer from the top]hereinafter

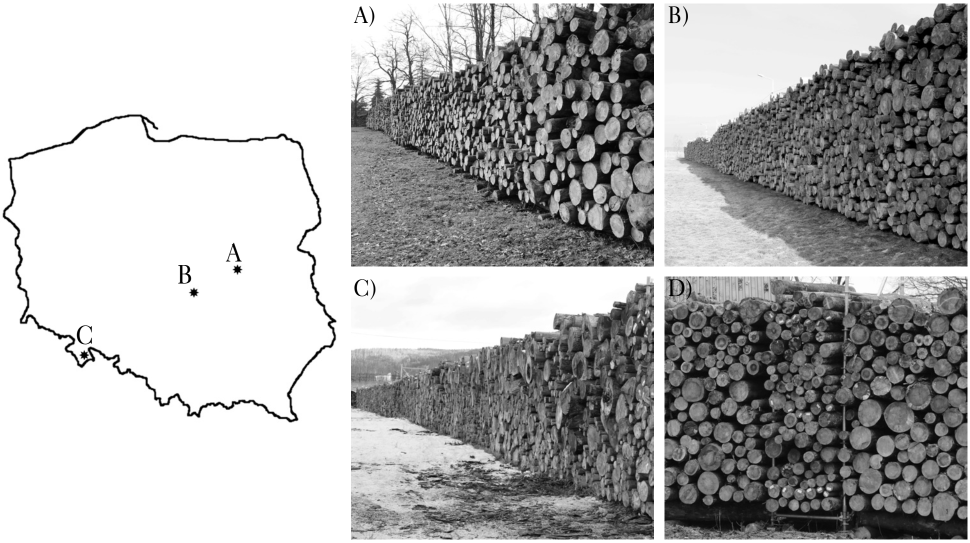

Fig. 1.
Location of experimental depots
Note: A – landing in Garwolin, B – landing in Spała, C – landing in Lądek-Zdrój, D – measuring basket

Fig. 2.
Measuring basket (A), the lower layer (B), the middle layer (C), the upper layer (D)

referred to as the upper layer (3)] (Fig. 2). The respective logs were permanently marked, and they were designated as 'test logs'. In each layer, 7 logs were selected, representing the range of diameters of the logs assembled in the log piles. A total of 21 test logs were placed in each basket. Each test log was assigned a specific number. Immediately after forming the stacks and filling the measuring baskets with wood, the first field work activities were carried out and the first measurements were conducted at the landing – in the so-called zero trial (trial 0). The following measurements were taken:

- Measuring the length of test logs (using a measuring tape – with the accuracy down to 1 cm)
- Measuring the diameter with the bark in the middle of the log's length, the measurement was performed twice, crosswise (using a calliper – with the accuracy down to 1 mm)
- The widths and lengths of traces of cut branches and bark damage were measured on the side of the logs.

The measurement was made with a measuring tape, determining the length and width of the stripped bark. These measurements were then used to calculate the bark stripping surface area. The calculations were made using the formula for the surface area of an ellipse:

$$P = \pi \cdot \frac{a}{2} \cdot \frac{b}{2} \tag{1}$$

where:

a – width of bark stripping,
b – length of bark stripping.

Then, these data were added to obtain the total area of the log not covered with bark. The value thus calculated was compared to the surface area of the entire log, to obtain the percentage of the log's surface that was not covered with bark. These measurements were carried out in each measurement trial, for each sample.

Additionally, at each timber landing, in each measuring basket, an electronic humidity and temperature recorder (HOBO Pro v2 – accuracy ±0.21°C and ±2.5% humidity) was placed in the middle of the log pile's height, in order to determine the variability of these features inside the log pile.

All the measurement procedures listed above were carried out in the landings 9 times, specifically: immediately after forming the stacks and filling the measuring baskets with wood (trial 0), and then at the following intervals: 6 (trial 1), 9 (2), 12 (3), 15 (4), 18 (5), 24 (6), 30 (7), and 36 (trial 8) months from trial zero.

Due to the fact that after applying the Shapiro-Wilk test, the null hypothesis about the normality of data distribution was rejected, the Mann-Whitney U test, the Kruskal-Wallis test, and the post-hoc multiple comparisons test were used in order to analyse the statistical significance of the differences. The ranges of data that were compared are presented in the Results. Statistica ver. 12 was used for statistical analyses (Kot *et al.* 2007; StatSoft, 2016). The significance level of p=0.05 was adopted in the statistical analyses.

Results

As a result of the analyses of pine wood carried out at landing A, we found that in subsequent trials, in each layer (1, 2, 3), the surface areas of the logs not covered with bark increased (Fig. 3). It can also be observed that in later trials the largest bark loss was recorded in layer 3 (the upper layer), smaller loss was recorded in layer 2 (the middle layer), and the smallest one was observed in layer 1 (the lower layer). In layer 3, the bark loss was quite rapid and in the 8th trial (after 36 months) it reached up to 95%. We also determined that, especially in layers 1 and 2, there were logs in which the loss of bark was small until the last trial, or the logs were completely devoid of bark from the start of the experiment (trial 0) (Table 1). Significant loss of bark on the logs resulted not only from the influence of external factors, but also from their being moved each

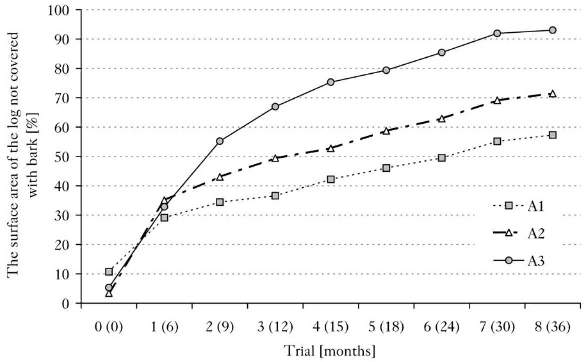

Fig. 3.
Changes in the surface area of the log not covered with bark in subsequent trials, in measurement layers (at timber landing A)
Note: 1 – the lower layer, 2 – the middle layer, 3 – the upper layer

Table 1.
Statistical characteristics of bark losses at the landing A

Landing/ Layer	Trial [months]	Average [%]	Medium [%]	Min [%]	Max [%]	Standard deviation [%]	Coefficient of variation [%]
A1	0 (0)	10.72	1.39	0.09	100.00	22.54	210.34
	1 (6)	29.13	21.53	0.23	100.00	31.15	106.93
	2 (9)	34.45	22.78	0.22	100.00	32.10	93.17
	3 (12)	36.61	26.83	0.23	100.00	32.40	88.52
	4 (15)	42.21	35.36	0.37	100.00	32.99	78.17
	5 (18)	46.07	43.14	0.50	100.00	33.08	71.80
	6 (24)	49.51	45.89	0.65	100.00	31.84	64.31
	7 (30)	55.14	58.77	0.97	100.00	31.27	56.71
	8 (36)	57.31	67.70	0.97	100.00	30.18	52.65
A2	0 (0)	3.44	2.21	0.60	13.88	3.51	102.18
	1 (6)	35.11	28.83	1.72	94.80	31.95	91.00
	2 (9)	43.05	38.65	1.90	100.00	33.88	78.70
	3 (12)	49.41	49.30	1.97	100.00	34.29	69.40
	4 (15)	52.76	51.76	2.16	100.00	33.00	62.56
	5 (18)	58.72	59.93	2.32	100.00	32.84	55.93
	6 (24)	62.90	66.48	2.94	100.00	30.50	48.50
	7 (30)	69.14	78.40	3.20	100.00	28.41	41.08
	8 (36)	71.45	82.31	3.87	100.00	27.04	37.85
A3	0 (0)	5.33	2.78	0.00	34.37	8.28	155.28
	1 (6)	32.83	13.14	1.39	100.00	35.36	107.69
	2 (9)	55.20	47.01	15.68	100.00	31.77	57.55
	3 (12)	66.97	72.03	20.11	100.00	29.04	43.36
	4 (15)	75.32	90.56	33.54	100.00	24.69	32.78
	5 (18)	79.37	92.40	44.24	100.00	20.95	26.39
	6 (24)	85.42	92.90	58.26	100.00	15.87	18.58
	7 (30)	91.94	94.95	66.07	100.00	10.37	11.28
	8 (36)	93.03	95.45	68.45	100.00	8.85	9.51

Note: 1, 2, 3 – layer numbers

time during subsequent trials. Using the Mann-Whitney U test, significant differences were demonstrated between bark loss at the beginning of the study (trial 0) and at the end of the study (trial 8), in individual layers (Table 2). The Kruskal-Wallis test also showed significant differences in bark loss between individual layers in trial 8 (H=20.548; p<0.001). However, when we refined the analysis by the application of a *post-hoc* test, we have found that only layer 3 (the upper layer) differed significantly from layer 2 (the middle layer) (p=0.011), and layer 1 (the lower layer) (p<0.001). By contrast, layers 1 and 2 did not differ significantly (p=0.383).

As a result of the analyses of pine wood conducted at landing B, it was found, similarly to landing A, that in subsequent tests, in each layer (1, 2, 3), the area of the logs not covered with bark increased (Fig. 4, Table 3). Bark loss in all analysed layers was similar, and the differences between trial 0 and trial 8 ranged between 30% and 50%. However, it is noticeable that the amount of bark falling off on the logs in layer 3 was slightly greater than in the other layers. After applying the Mann-Whitney U test, significant differences were found between the bark loss at the beginning of the study (trial 0) and at the end of the study (trial 8), in individual layers (Table 4), while the Kruskal-Wallis test did not show any statistically significant differences in the bark loss between individual layers in trial 8 (H=5.152; p=0.076).

Similarly to the previous landings, at landing C it was found, with respect to spruce wood, that in subsequent trials, in each layer (1, 2, 3), the surface areas of the logs not covered with bark gradually increased (Fig. 5). Bark defects in most of the analysed cases were small, and the differences between trial 0 and trial 8 (*i.e.* after 36 months) ranged between 30 and 40%. The smallest average bark loos was recorded in the lower layer (1), while in the middle (2) and the upper layers (3) the loss was similar. It is also noticeable that in all layers there were logs in which the bark covered almost the entire surface until the very end (trial 8), as well as logs which were completely bark-free from the very beginning of the study (trial 0) (Table 5). After applying the Mann-Whitney U test, significant differences were found between the bark loss at the beginning of the study (trial 0) and at the end of it (trial 8), in individual layers (Table 6), while the Kruskal-

Table 2.

Results of the Mann-Whitney U test for respective trials and layers at the landing A

Trial/ Layer	U	Z	p
A01-A81	43.000	–4.453	0.000
A02-A82	5.000	–5.408	0.000
A03-A83	0.000	–5.534	0.000

Note: 0, 8 – trial number, 1, 2, 3 – layer numbers

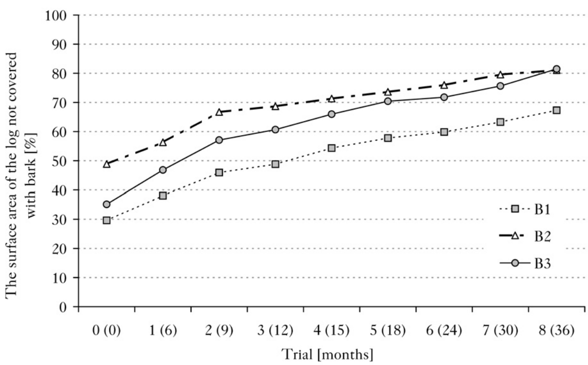

Fig. 4.

Changes in the surface area of the log not covered with bark in subsequent trials, in measurement layers (at timber landing B)

Wallis test did not show any statistically significant differences in bark loss between individual layers in trial 8 (H=6.363; *p*=0.051).

In subsequent statistical analyses, the significance of differences between the same layers but in different timber landings was tested. It turned out that layers 1 (the lower layer) and 2 (the middle layer) did not differ significantly between the landings (H=3.888; *p*=0.143 and H=2.957; *p*=0.228, respectively). By contrast, it was found that layers 3 (the upper layers) differed significantly (H=6.929; *p*=0.031). However, when we expanded this analysis with a *post-hoc* test, it was

Table 3.
Statistical characteristics of bark losses at the landing B

Landing/ Layer	Trial [months]	Average [%]	Medium [%]	Min [%]	Max [%]	Standard deviation [%]	Coefficient of variation [%]
B1	0 (0)	29.64	19.90	0.90	100.00	30.19	101.86
	1 (6)	38.06	34.88	3.14	100.00	29.55	77.64
	2 (9)	45.94	45.68	3.37	100.00	29.10	63.34
	3 (12)	48.82	48.26	3.26	100.00	28.52	58.42
	4 (15)	54.34	53.31	3.68	100.00	27.63	50.86
	5 (18)	57.78	61.59	4.04	100.00	27.74	48.02
	6 (24)	59.87	63.55	4.83	100.00	27.77	46.38
	7 (30)	63.28	66.19	6.74	100.00	26.02	41.11
	8 (36)	67.32	69.44	8.26	100.00	25.20	37.44
B2	0 (0)	48.86	36.22	1.24	100.00	37.77	77.30
	1 (6)	56.32	42.14	4.11	100.00	34.15	60.63
	2 (9)	66.72	74.69	10.60	100.00	32.12	48.14
	3 (12)	68.68	81.46	14.70	100.00	31.46	45.81
	4 (15)	71.31	82.61	20.22	100.00	30.01	42.08
	5 (18)	73.63	86.03	26.87	100.00	27.81	37.77
	6 (24)	75.99	90.37	29.29	100.00	26.81	35.28
	7 (30)	79.57	94.57	38.00	100.00	23.56	29.61
	8 (36)	81.09	95.09	40.94	100.00	22.02	27.16
B3	0 (0)	35.12	29.08	0.27	100.00	28.70	81.70
	1 (6)	46.83	48.46	0.76	100.00	28.11	60.01
	2 (9)	57.09	61.17	0.80	100.00	25.43	44.54
	3 (12)	60.67	65.94	2.32	100.00	25.54	42.10
	4 (15)	65.97	72.34	3.57	100.00	25.40	38.49
	5 (18)	70.42	72.66	5.00	100.00	25.35	36.00
	6 (24)	71.78	74.00	5.96	100.00	24.58	34.24
	7 (30)	75.65	85.12	12.76	100.00	24.01	31.74
	8 (36)	81.48	86.18	46.04	100.00	18.43	22.62

Note: 1, 2, 3 – layer numbers

Table 4.
Results of the Mann-Whitney U test for respective trials and layers at the landing B

Trial/ Layer	U	Z	p
B01-B81	75.000	–3.648	0.000
B02-B82	117.000	–2.591	0.010
B03-B83	50.000	–4.276	0.000

Note: 0, 8 – trial number, 1, 2, 3 – layer numbers

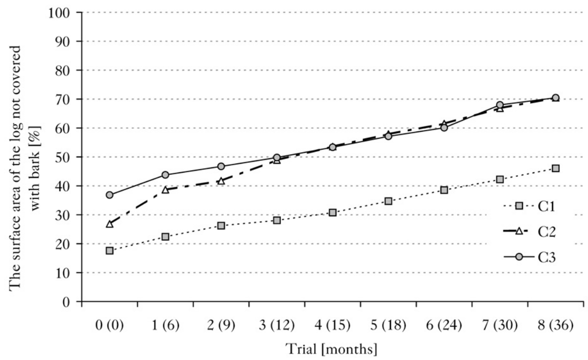

Fig. 5.
Changes in the surface area of the log not covered with bark in subsequent trials, in measurement layers (at timber landing B)

Table 5.
Statistical characteristics of bark losses at the landing C

Landing/ Layer	Trial [months]	Average [%]	Medium [%]	Min [%]	Max [%]	Standard deviation [%]	Coefficient of variation [%]
C1	0 (0)	17.58	8.19	0.23	100.00	24.01	136.55
	1 (6)	22.42	10.11	0.50	100.00	27.52	122.75
	2 (9)	26.24	12.81	0.70	100.00	29.31	111.69
	3 (12)	28.08	15.34	0.88	100.00	29.82	106.21
	4 (15)	30.77	17.18	2.30	100.00	30.31	98.50
	5 (18)	34.72	18.41	2.55	100.00	31.87	91.80
	6 (24)	38.53	21.48	4.00	100.00	33.76	87.63
	7 (30)	42.23	25.64	7.14	100.00	34.24	81.08
	8 (36)	46.06	27.22	8.76	100.00	35.28	76.60
C2	0 (0)	26.85	15.66	1.46	100.00	28.73	106.98
	1 (6)	38.67	35.33	1.98	100.00	31.57	81.64
	2 (9)	41.75	41.24	4.74	100.00	29.32	70.22
	3 (12)	48.92	52.19	5.12	100.00	32.50	66.43
	4 (15)	53.58	63.65	5.75	100.00	32.79	61.20
	5 (18)	57.90	69.55	6.56	100.00	32.70	56.47
	6 (24)	61.51	72.23	8.43	100.00	32.68	53.14
	7 (30)	66.85	82.68	10.48	100.00	32.33	48.37
	8 (36)	70.46	87.03	15.05	100.00	32.17	45.66
C3	0 (0)	36.84	34.10	0.11	100.00	34.97	94.91
	1 (6)	43.78	39.47	0.48	100.00	36.74	83.92
	2 (9)	46.73	47.00	0.49	100.00	36.21	77.49
	3 (12)	49.79	49.58	0.96	100.00	34.88	70.05
	4 (15)	53.35	57.64	1.10	100.00	34.71	65.06
	5 (18)	57.11	62.28	1.57	100.00	34.94	61.17
	6 (24)	60.08	71.99	2.16	100.00	34.76	57.86
	7 (30)	67.99	80.27	6.05	100.00	31.24	45.94
	8 (36)	70.47	77.51	7.07	100.00	30.19	42.84

Note: 1, 2, 3 – layer numbers

found that only layer 3 (the upper layer) from landing A differed significantly from layer 3 from landing C (A3-C3) (p=0.042). By contrast, there were no significant differences between the upper layers (3) from landing A versus landing B (A3-B3) (p=0.158), or from landing B versus landing C (B3-C3) (p=1.000).

Table 6.
Results of the Mann-Whitney U test for respective trials and layers at the landing C

Trial/ Layer	U	Z	p
C01-C81	82.000	–3.471	0.001
C02-C82	70.000	–3.773	0.000
C03-C83	114.000	–2.667	0.008

Note: 0, 8 – trial number, 1, 2, 3 – layer numbers

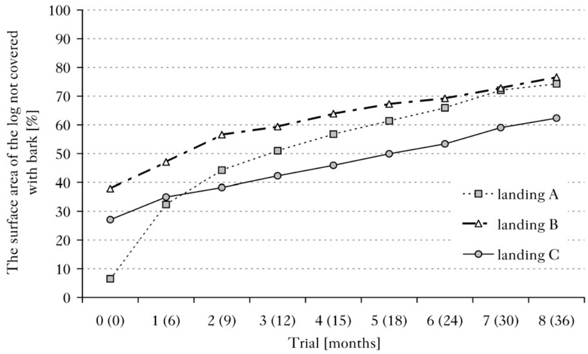

Fig. 6.
Changes in the surface area of the log that is not covered with bark, in subsequent trials, in the studied landings

Having analysed the bark loss on test logs in the examined landings, it was determined that in landings B and C average bark loss was small during the examined period (36 months) (Fig. 6). They amounted to approximately 40%. However, in landing A, the average loss of bark was greater, and amounted on average to approximately 70% of the log surface area. It was also determined that in all layers there were logs in which the bark covered almost the entire surface until the very end of the study (trial 8), as well as logs which were completely bark-free from the beginning of the study (trial 0) (Table 7). Upon applying the Mann-Whitney U test, significant differences were found between the bark loss at the beginning of the study (trial 0) and at the end of the study (trial 8) in individual landings (Table 8), while the Kruskal-Wallis test did not reveal any statistically significant differences in the bark loss between landings in trial 8 ($H=4.553$; $p=0.103$).

Discussion

The present study examined how long bark can remain on wood that has been stored in a landing for a prolonged period of time. It was determined that after 36 months of storing, on average, about 30-40% of the bark remained on the logs. However, we need to take into account the fact that in the case of such dead wood as was used in the trials, already at the stage of stacking the log piles, some logs would have been completely devoid of bark. There would also have been logs that remain completely covered with bark by the end of the storage period. This is due to the fact that dead trees remain in the stand for some time until they are removed. They are affected by unfavourable external factors (rainfall, wind, temperature), which cause the bark to fall off. Additionally, mechanical damage that occurs during felling and transport of these trees increases the loss of bark on the logs. We also need to bear in mind that the tested logs were removed and then reinserted into the measuring baskets during each trial, which resulted in mechanical damage to the bark and in some of the bark falling off. We should assume that the share of bark on wood stored in timber landings (without repeated relocation) would typically be much greater. Unfortunately, this amount cannot be estimated precisely because each movement of the wood

Table 7.
Statistical characteristics of bark losses in all three landings combined

Landing/ Layer	Trial [months]	Average [%]	Medium [%]	Min [%]	Max [%]	Standard deviation [%]	Coefficient of variation [%]
A	0 (0)	6.50	2.32	0.00	100.00	14.13	217.52
	1 (6)	32.36	20.30	0.23	100.00	32.43	100.22
	2 (9)	44.23	40.04	0.22	100.00	33.19	75.04
	3 (12)	50.99	47.48	0.23	100.00	33.87	66.42
	4 (15)	56.76	55.56	0.37	100.00	33.06	58.24
	5 (18)	61.39	59.93	0.50	100.00	32.15	52.38
	6 (24)	65.94	71.45	0.65	100.00	30.52	46.29
	7 (30)	72.07	79.41	0.97	100.00	29.05	40.31
	8 (36)	73.93	84.02	0.97	100.00	27.82	37.63
B	0 (0)	37.87	29.08	0.27	100.00	32.96	87.02
	1 (6)	47.07	41.76	0.76	100.00	31.13	66.14
	2 (9)	56.58	53.70	0.80	100.00	29.80	52.66
	3 (12)	59.39	62.02	2.32	100.00	29.32	49.37
	4 (15)	63.87	69.54	3.57	100.00	28.21	44.17
	5 (18)	67.28	70.60	4.04	100.00	27.43	40.78
	6 (24)	69.21	72.48	4.83	100.00	26.88	38.84
	7 (30)	72.83	76.69	6.74	100.00	25.15	34.53
	8 (36)	76.63	83.18	8.26	100.00	22.69	29.61
C	0 (0)	27.09	11.81	0.11	100.00	30.16	111.31
	1 (6)	34.96	21.48	0.48	100.00	32.95	94.26
	2 (9)	38.24	29.59	0.49	100.00	32.48	84.93
	3 (12)	42.27	39.10	0.88	100.00	33.50	79.27
	4 (15)	45.90	46.63	1.10	100.00	33.88	73.82
	5 (18)	49.91	56.65	1.57	100.00	34.40	68.93
	6 (24)	53.37	59.54	2.16	100.00	34.85	65.29
	7 (30)	59.02	65.76	6.05	100.00	34.26	58.04
	8 (36)	62.33	69.72	7.07	100.00	34.12	54.74

Note: 1, 2, 3 – layer numbers

Table 8.
Results of the Mann-Whitney U test for respective trails, for particular landings

Trial/ Layer	U	Z	p
A0-A8	141.000	–8.992	0.000
B0-B8	782.000	–5.865	0.000
C0-C8	854.000	–5.513	0.000

will cause smaller or larger mechanical damage, which will result in detachment of the bark. Depending on the purpose or designation of such timber, this is of critical importance, because wood intended for industrial processing must be stripped of bark, while wood intended for fuel does not require such treatment. In the first case, a larger share of bark increases production costs and also requires space for its storage; in the second case, the amount of fuel increases because the volume of bark is not included in the volume of wood. And as already mentioned in the introduction, the calorific value of bark is often close to the calorific value of wood. In pine, the calorific value of completely dry bark is slightly lower than that of wood (bark 20.20

MJ/kg, wood 20.62 MJ/kg), and in spruce, it is slightly higher (bark 20.32 MJ/kg, wood 20.08 MJ/kg) (Prosiński, 1984; Jeżowski, 2003; Neiva *et al*., 2018). Unfortunately, bark obtained by stripping in industrial plants is often high in moisture, which significantly reduces its calorific value. Another disadvantage of bark is its high ash content, which is on average about 2.14% (Antkowiak, 1997), and for coniferous trees even as much as 3.9% of the dry fuel mass (Gawlicki *et al*., 2018). Some authors (Miranda *et al*., 2012) report the bark ash content to be 3.3% for spruce and even as much as 4.6% for pine.

Having said that, it was observed (Routa *et al*., 2021) that the moisture of pine bark after 2 months of storage decreased on average by 16% (from 47% at the beginning of the study to 31% after 2 months in storage). On the other hand, the average ash content increased slightly: from 1.89% in fresh bark to 1.97% after 2 months of storage. The calorific value of bark also increased: from 9.19 MJ/kg to 12.74 MJ/kg, which resulted from a decrease in its moisture content. A similar trend was also observed in the study of Lehtikangas (2001). It was found that in fresh spruce and pine bark (a mixture of 60% spruce, 40% pine), the ash content was on average about 2.65%; after 2 months of storage it was 3.0%; and after 6 months it went up to 6.94%. High ash content may result from mineral impurities but also from the loss of other compounds during raw material storage. Air pollution may also affect ash content in the bark. Saarela *et al*. (2005) demonstrated that ash content in pine bark sampled close to the petroleum refinery (4.08%) is more than twice as high as in bark sampled 20 km from the plant (1.36%). Nevertheless, bark can be a valuable fuel-wood, both in crushed form and in the form of pellets (Lehtikangas, 2001; Filbakk *et al*., 2011; Król and Borsukiewicz-Gozdur, 2014).

Conclusions

As a result of conducted analyses, the following conclusions were drawn:

- Logs located in the upper layer (3) of the pile showed the largest loss of bark (by about 20-30% higher than other layers). During field research, it was observed that precipitation penetrated the upper layers of wood in the log pile more easily, which caused cyclical changes in bark moisture and, as a result, the bark fell off much more easily. The rainfall did not penetrate the lower layers, which made the logs dry out much more and the bark adhered more strongly to the logs side surface.
- In all landings, bark fell off at a similar rate (by approximately 10% every 6 months), and after 36 months of timber storage, the share of bark on the logs was similar (about 30%), both on pine and spruce wood.
- On the tested wood logs, both in trial 0 and in trial 8 (after 36 months), there were logs completely devoid of bark (about 40%) and logs completely covered with bark (about 5%).
- After 36 months of storage, approximately 30% of the bark remained on the logs. Based on literature data providing the share of bark in the trunk volume, it can be determined that after this period, the volume of bark remaining on the logs will be approximately 3% of the volume of the stored wood. When using this wood for fuel purposes, it is a significant 'added' value that is not included in the wood volume.

Autors' contributions

K.M. – conceptualization, methodology, formal analysis, material collection, statistical analyses, investigation, writing – original draft preparation; J.M.S. – conceptualization, methodology, manuscript review and editing, funding acquisition; R.W. – conceptualization, methodology, material collection, manuscript review and editing; M.B.G. – conceptualization, methodology,

material collection, manuscript review and editing; A.B. – conceptualization, methodology, manuscript review and editing; D.K. – conceptualization, formal analysis, material collection, statistical analyses; A.S. – conceptualization, formal analysis, material collection, statistical analyses, manuscript review and editing; Ł.M. – formal analysis, material collection, statistical analyses; A.G. – formal analysis, material collection, statistical analyses.

Conflict of interest

The authors declare no conflict of interest.

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STRESZCZENIE

Analiza dynamiki zmian ubytków kory na pobocznicy drewna posuszowego w wyniku długotrwałego przelegiwania drewna na składnicy

W ostatnich latach obserwuje się znaczne ilości wydzielającego się posuszu, nawet sosnowego, co wynika z częstych okresów suszy i obniżania się poziomu wód gruntowych. Stanowi to rocznie średnio około 15% drewna pozyskiwanego w Lasach Państwowych (Statistics Poland 2022). Drewno takie musi czasami przelegiwać na składnicach przez dłuższy czas. Często jest ono złej jakości i przeznaczane jest do celów opałowych – wówczas kora jest wartością dodaną, której nie wlicza się w miąższość drewna. W związku z tym w niniejszej pracy przeprowadzono analizę zmian ubytków kory na pobocznicy drewna posuszowego, które przez dłuższy czas przeleguje na składnicy. W 3 regionalnych dyrekcjach Lasów Państwowych zostały założone składnice drewna posuszowego (po około 600 m^3): w RDLP Warszawa składnica w Garwolinie (drewno sosnowe) (A), w RDLP Łódź składnica w Spale (drewno sosnowe) (B) oraz w RDLP Wrocław składnica w Lądku-Zdroju (drewno świerkowe) (C) (ryc. 1). Na etapie formowania mygieł zostały założone punkty pomiarowe zwane koszami pomiarowymi. Przestrzeń wewnętrzna kosza pomiarowego została wypełniona drewnem prostym, bez widocznej krzywizny, co ułatwiało pomiary i zmniejszało ryzyko popełnienia błędu. W każdej składnicy umiejscowiono 3 kosze pomiarowe z drewnem posuszowym (ryc. 2). W każdym koszu pomiarowym złożonym z wielu warstw ułożono wałki próbne w 3 warstwach, tj. drugiej od dołu, zwanej dalej dolną (1); w środku wysokości mygły, tzw. środkowej (2) oraz drugiej od góry, tzw. górnej (3). W każdej warstwie wytypowano po 7 wałków reprezentujących zakres średnic wałków złożonych w mygłach. Bezpośrednio po uformowaniu mygieł i wypełnieniu koszy pomiarowych drewnem przeprowadzono na składnicy pomiary długości wałków próbnych, średnicy z korą w środku długości wałka, szerokości i długości miejsc po odciętych gałęziach oraz wielkości uszkodzeń kory na pobocznicy wałków. Wszystkie prace pomiarowe prowadzone były na składnicach 9-krotnie, tj. bezpośrednio po uformowaniu mygieł i wypełnieniu drewnem koszy pomiarowych (próba 0), a następnie w odstępach: 6 (próba 1), 9 (2), 12 (3), 15 (4), 18 (5), 24 (6), 30 (7) i 36 (8) miesięcy od próby zerowej.

W wyniku przeprowadzonych analiz stwierdzono, że wraz z wydłużaniem się okresu przelegiwania drewna ubytki kory na wałkach zwiększały się, a różnice te między próbą 0 a próbą 8 (po 36 miesiącach) były statystycznie istotne (tab. 2, 4 i 6). Stwierdzono także – zarówno dla drewna sosnowego, jak i świerkowego – że wałki położone w górnej warstwie (3) wykazały największe ubytki kory (ryc. 3-5; tab. 1, 3 i 5). Wynikało to głównie z większej zmienności wilgotności, gdyż do górnych warstw drewna w mygle łatwiej przenikały opady, silniejsze było też oddziaływanie wiatru i słońca, co powodowało cykliczne zmiany wilgotności kory i w efekcie znacznie łatwiejsze jej odpadanie. W warstwach dolnych przesuszenie wałków było o wiele większe, a zmienność wilgotności była mniejsza, przez co kora silniej przylegała do pobocznicy wałków.

Analizowano również różnice między tymi samymi warstwami, ale na różnych składnicach. Wykorzystano do tego celu test Kruskala-Wallisa i test *post hoc*. Okazało się, że warstwy 1 (dolne) i 2 (środkowe) nie różnią się istotnie pomiędzy składnicami. Stwierdzono natomiast, że warstwy 3 (górne) różnią się istotnie. Jednak pogłębiając tę analizę testem *post hoc*, stwierdzono, że tylko warstwa 3 (górna) z Garwolina (A3) różni się istotnie od warstwy 3 z Lądka-Zdroju. Na wszystkich składnicach odpadanie kory postępowało w podobnym tempie i po 36 miesiącach przelegiwania drewna udział kory na wałkach był zbliżony: zarówno na drewnie sosnowym, jak i świerkowym (ryc. 6). Na badanych wałkach drewna, zarówno w próbie 0, jak i w próbie 8, stwierdzano wałki prawie całkowicie pozbawione kory oraz całkowicie pokryte korą (tab. 7), a różnice były statystycznie istotne (tab. 8). Znaczny ubytek kory na wałkach wynikał nie tylko z oddziaływania czynników zewnętrznych, ale także z każdorazowego przemieszczania ich podczas kolejnych prób. Należy przypuszczać, że udział kory na wałkach, które nie są tak często przemieszczane, będzie o wiele większy.