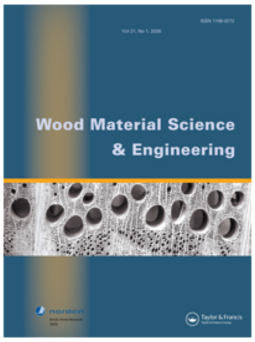

Taylor & Francis
Taylor & Francis Group

Wood Material Science & Engineering

ISSN: 1748-0272 (Print) 1748-0280 (Online) Journal homepage: www.tandfonline.com/journals/swoo20

Dry storage of Norway spruce log sections – a field experiment to assess wood quality changes

Jan-Frederik Trautwein , Lukas Emmerich , Hannes Fritsching , Holger Militz , Stefanie Wieland & Christian Brischke

To cite this article: Jan-Frederik Trautwein , Lukas Emmerich , Hannes Fritsching , Holger Militz , Stefanie Wieland & Christian Brischke (27 Feb 2026): Dry storage of Norway spruce log sections – a field experiment to assess wood quality changes, Wood Material Science & Engineering, DOI: 10.1080/17480272.2026.2635658

To link to this article: https://doi.org/10.1080/17480272.2026.2635658

Published online: 27 Feb 2026.

WOOD MATERIAL SCIENCE & ENGINEERING
https://doi.org/10.1080/17480272.2026.2635658

Taylor & Francis
Taylor & Francis Group

ORIGINAL ARTICLE

OPEN ACCESS Check for updates

Dry storage of Norway spruce log sections – a field experiment to assess wood quality changes

Jan-Frederik Trautwein[a], Lukas Emmerich[b], Hannes Fritsching[a], Holger Militz[a], Stefanie Wieland[b] and Christian Brischke[c]

[a]Faculty of Forest Sciences and Ecology, Wood Biology and Wood Products, University of Goettingen, Goettingen, Germany; [b]Wald und Holz NRW, Centre of Forest and Wood Industry, Team Wood-Based Industries, Olsberg, Germany; [c]Thünen Institute of Wood Research, Hamburg, Germany

ABSTRACT
Mass infestation of Norway spruce stands by bark beetles in recent years has led to a massive increase in the volume of calamity timber. Often, spruce snags remain in the forest for extended periods and are unintentionally stored there for up to several years. To prevent loss of quality, the dry snags were often moved to dry storage, piled up without ground contact and covered with PVC-coated, weather-resistant and waterproof polyester fabric, before being supplied to the sawmill industry. This study investigated changes in the quality of spruce logs due to dry storage, depending on the length of the previous standing storage duration. As expected, quality changes occurred, but most of the wood remained suitable for sawing and could be used as a material in the sawmill industry. Hence, dry storage offers a simple, less elaborate and cost-effective conservation technique for standing-stored, and thus pre-dried beetle-infested calamity timber. Secondary infestation with insects occurred, but was limited to the outer stem zones. Standing-stored wood is characterised by a lower initial moisture content, and hence it reaches moisture content below cell wall saturation earlier compared to wood that was still alive.

ARTICLE HISTORY
Received 23 November 2025
Accepted 17 February 2026

KEYWORDS
Bark beetle; calamities; conservation; monitoring; roundwood quality; standing storage

1. Introduction

Recently, Central European Norway spruce (*Picea abies*) forests have been affected by severe bark-beetle calamities. In Germany, a total area of > 500,000 ha was put forth during the period 2018–2024 (BMEL 2024). In Germany, the Sauerland region and Harz Mountains registered the largest amounts of calamity timber during that period. As a consequence, the standing volume of Norway spruce forests in North Rhine-Westphalia decreased by up to 60% (MLV NRW 2024). In 2018, the winter storm “Friederike” followed by an extreme summer drought brought forth a bark beetle calamity in North Rhine-Westphalia, which had not been there since 1947 (Niesar *et al.* 2018). The consequences: Massive quantities of calamity timber were available and exceeded both harvesting, conservation and processing capacities as well as the regional demand for Norway spruce wood. Thus, calamity-adapted and feasible conservation techniques are needed (Brischke *et al.* 2024, Emmerich *et al.* 2025) to preserve logs as a key resource for the material utilizations of wood along regional supply chains. In this context, dry storage of standing-stored, beetle-infested spruce logs was studied in order to find a calamity-adapted, feasible, and cost-effective conservation technique for beetle-infested calamity timber.

Calamity timber can differ significantly from regularly harvested wood. Although storm-felled wood is usually still fresh, it can show more mechanical defects, and beetle-infested trees dry out before harvest. Depending on the length of the snags remaining in the forest before harvesting, they lose their bark to varying degrees, dry out, form cracks along their axes, or suffer secondary damage from wood-boring insects or wood-destroying fungi (Hýsek *et al.* 2021, Trautwein *et al.* 2025b). Owing to capacity constraints and limited storage space, beetle-infested spruce trees are often left standing in forests for a certain period of time. During this upright storage, they dry out, but if the time becomes too long, they can lose quality, for example due to rot damage. However, if they are felled in time and removed from the forest, they are suitable for so-called calamity wood dry storage.

Trautwein *et al.* (2025a) reviewed methods for the storage and conservation of roundwood with an emphasis on calamity wood and against the background of the current framework conditions. Wet storage allows several years of conservation but is not sustainable because of the decreasing availability of water and soil contamination due to washouts (Persson and Elowson 2001, Jonsson 2004, 2012). Foil storage using the “Baden-Württemberg method”, when a pile is completely enclosed with foil, is more reliable but also more expensive than the “Swiss method” (no foil between pile and ground) because of the complete exclusion of oxygen (Brischke *et al.* 2021). Both methods have limitations with respect to storage of logs from beetle-infested trees. Earth storage is a new approach with successful oxygen reduction (Becker 2022), but

CONTACT Christian Brischke christian.brischke@thuenen.de Thünen Institute of Wood Research, Leuschnerstr. 91d, Hamburg D-21031, Germany

further research regarding wood moisture is required. Leaving dead trees unharvested in the forest, the so-called "standing storage", preserves wood by drying, but there is currently a lack of scientific findings. The standing storage duration (SSD) therefore refers to the time since the tree died. Live storage, in which the root plate of thrown trees remains on the trunk, preserves wood quality over a vegetation period (Bücking *et al.* 1997, Jonsson 2007). "Calamity wood dry storage" is a special form of dry storage and is particularly used for storage of bark beetle-infested Norway spruce from months to years. This method was developed out of necessity. While standing trees stored in forests were in danger of rotting, sawmills lacked sufficient capacity to process them. Therefore, it was necessary to find options for temporary storage, so the sawmill industry created temporary storage facilities near the mills. However, knowledge about the potential quality preservation in such dry storage facilities and the causes of possible quality losses remains largely unexplored. In addition to wood moisture content (MC) and quality prior to storage, site factors such as humidity, wind direction and solar radiation should be considered when setting up a dry storage pile.

Therefore, this study aimed to determine the extent to which the initial wood quality can be retained in dry storage. The primary objective is to maintain the sawability of the logs in order to enable high-quality wood products, such as for construction applications. In addition, the effect of the initial MC on the protection of the spruce logs was investigated and finally we aimed to gain knowledge about the drying process of roundwood during dry storage with respect to intra-stem differences, for example between sapwood and heartwood zones. To achieve this, both gravimetric and electrical resistance measurements were carried out at different storage time intervals.

2. Material and methods

2.1. Dry storage

Dry storage piles – covered with a PVC-coated, UV-resistant and waterproof polyester fabric (high-strength tarpaulin fabric, approximately 680 g/m^2, tear strength of 3000 N) – were installed at a test site (51°20'10.7"N; 8°29'15.4"E) close to Olsberg, Germany (Figure 5, Table 1). The aspired protective mechanism was to keep the MC (based on dry mass) in stored logs below the critical level for fungal growth and decay, and by that prevent a loss in quality and mechanical properties. For a period of 30 months (February 2023–July 2025), MC inside the logs was monitored permanently by

Table 1. Description of the source material (logs; focus: Ø ≥ 20 cm for sawn timber production for construction purposes) for the dry storage treatments at the test site close to Olsberg. The storage period lasted from 9 February 2023 to 11 June 2025.

Tree state (–)*	SSD (years)	Crown condition (–)	Bark condition (–)	*n* logs Ø ≥ 20 cm	*n* logs Ø < 20 cm
Living	/	Green needles	Attached	32	56
Dead 0	0 years	Discoloured needles	Loose	26	43
Dead 0.5	0.5 years	No needles	Off	34	41

*State at harvesting and installation of the dry storage pile.

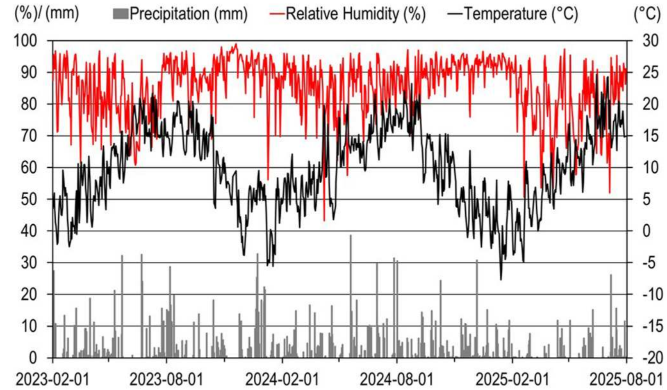

Figure 1. Climatic conditions at the test site in Olsberg-Steinhelle from 1 February 2023 until 1 August 2025: Ambient temperature (°C), relative humidity (%) and precipitation (mm) measured by a local weather station close to the testing site in Olsberg-Steinhelle, which is exposed in a valley location at 348 m above sea level.

electrical resistance measurements for both inner (20 mm depth) and outer (80 mm) sections. Weather conditions were recorded by a local weather station close to the testing site in Olsberg-Steinhelle, which was exposed in a valley location at 348 m above sea level (Figure 1).

Three logs per pile were equipped with MC sensors, a Thermofox universal datalogger and a connected Gigamodul (Scanntronik Mugrauer GmbH, Zorneding, Germany, Figure 5). In parallel, gravimetric MC measurements were performed at regular intervals after 0, 6, 10, 13, 19, 24 and 30 months of dry storage, and both monitoring techniques were evaluated.

2.2. Assessment of roundwood quality

The quality of 3 m Norway spruce log sections was assessed prior to and after the dry storage with regard to its quality according to the General Agreement for Trading Logs (Rahmenvereinbarung für den Rohholzhandel in Deutschland: RVR), which offers a use-neutral, nationwide quality assessment in Germany. The detachment of bark, thus the amount of the log´s surface area being covered with bark, radial cracking, and decay were assessed separately. In particular, log sections of choice (Focus: Ø ≥ 20 cm) were assessed according to Appendix III-a "Quality assessment of logs: Spruce/ Fir" of the RVR under consideration of the quality criteria listed in Table 2 (RVR, Plattform Forst & Holz 2024) and exemplary shown in Figure 2.

2.3. Assessment of sawn wood quality

In addition to the assessment of roundwood quality, the logs were sawn to planks, and the quality of the 65 mm thick middle planks was assessed visually with respect to the occurrence of red streakiness, blue staining and fungal decay on the basis of the surface area (Figure 3).

Based on the percentage of the affected surface area of the middle planks, the boards were graded according to a 5-step scale summarised in Table 3 (non-standardised method) regarding red streakiness and blue staining. The occurrence of fungal decay was also recorded, assessed visually, and with the help of a pick-test according to EN 252 (2015).

Table 2. Quality assessment classes and criteria for Norway spruce logs based on General Agreement for Trading Logs (RVR, Plattform Forst & Holz 2024).

Quality class**	Description	Cracking	Fungal decay/ rotting*	Wood-boring insects	Bark breeding insects
A	Excellent quality	≤ 1/4 of the diameter	Not accepted	Not accepted	No regulation
B	Normal quality, few imperfections	≤ 1/3 of the diameter	Not accepted	Not accepted	Freshly infested, no larvae grooves, bark attached, no staining
C	Normal quality, many imperfections	≤ 1/2 of the diameter	Not accepted	Not accepted	Larvae grooves accepted, superficial staining (blue stain), bark mainly attached, non-seasoned logs
D	Lower quality than A–C	Accepted	Accepted in the outer region*	< 2 mm (e.g. *T. lineatum*) accepted; > 2 mm (e.g. *Sirex, Cerambycidae*) not accepted	Blue stain and red streakiness are accepted, bark loose/detached, seasoned/dry logs, sound wood
IW	Industry wood, not sawable	Log sections occur worse than mentioned for quality class D			

*Pure discoloration accepted as long as no decay and impact on the wood structure occurs.
**80% of the cross section should be sawable and usable along the entire length of the log.
Further quality criteria according to Appendix III-a occurred (knots, eccentricity, warping, tapering and staining) but lay in the normal range, which corresponded to a quality class B assessment; thus, the latter were not decisive for the quality class assigned to the logs of choice (see Appendix III-a "Quality assessment of logs: Spruce/Fir" of the RVR, Plattform Forst & Holz 2024).

2.4. Gravimetric wood MC measurements

Gravimetric wood MC measurements were performed before and after storage. For MC determination prior to storage, each tree was cut into 3 m log sections, with an approximately 5 cm thick log disc between each section (Figure 4, incised beginning and end of the log section). The discs were packed airtight into plastic bags to avoid changes in the wood MC. A bar was cut from each disc, which was then divided into test specimens, to visualize the differences in initial wood MC (0 months) between heartwood and sapwood. Identical sampling procedure, i.e. differentiating between sap- and heartwood sections at both ends and along the stem axis at 50 cm intervals, was applied to logs measured during the dry storage. For this, one log was picked from the top of each dry storage pile after 10, 13, 19 and 24 months in order to determine the MC gravimetrically according to the procedure described before. After dry storage (30 months), the corresponding bars were cut from the middle planks of both heartwood and sapwood regions as shown in Figure 4 from each of the logs tested with a log Ø ≥ 20 cm. Each test specimen was weighed to the nearest 0.001 g, oven-dried at 103°C for 48 h, and then weighed again. Finally, the wood MC was determined according to EN 13183 (2002). A t-test for independent samples was applied to analyse statistically significant differences between

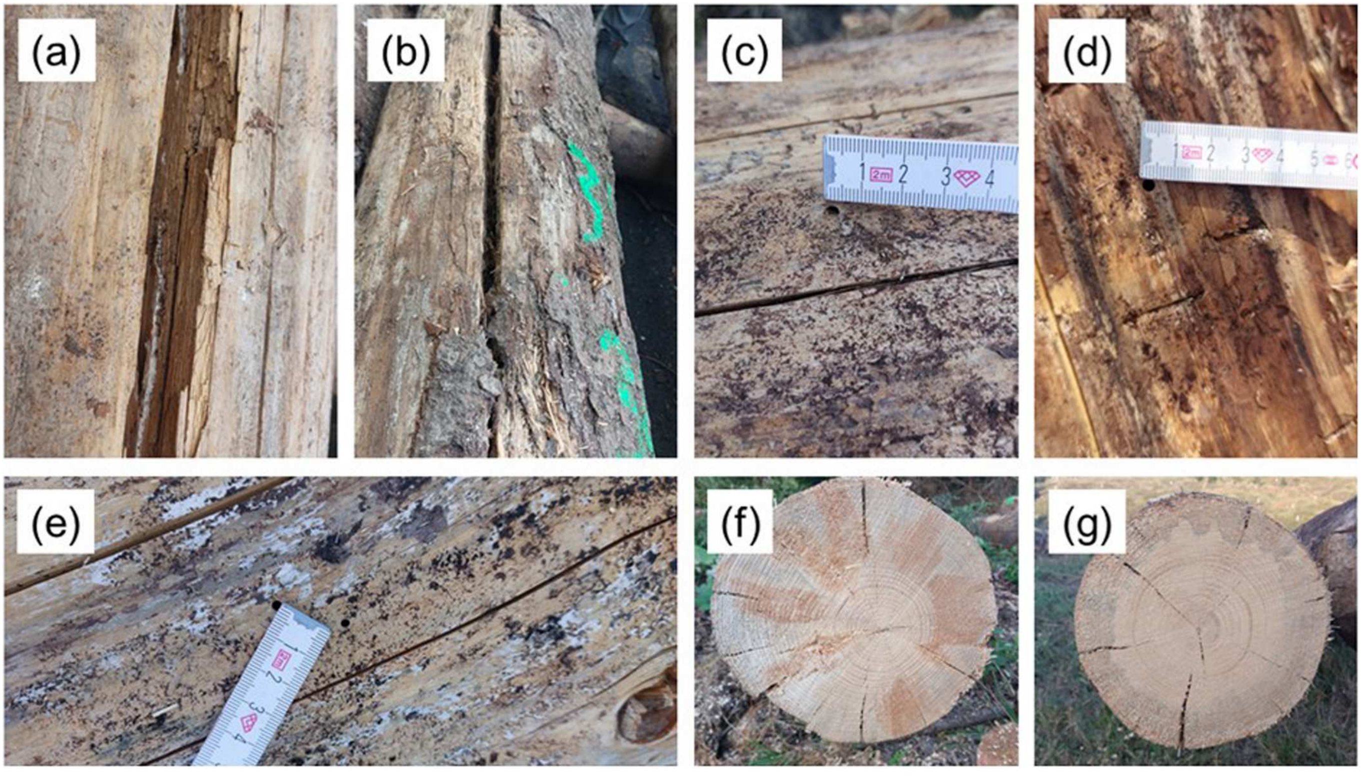

Figure 2. Quality criteria being considered for quality assessments of 3 m Norway spruce log sections:– (a) fungal decay, (b) radial cracking, attack by wood-boring insects such as (c) Cerambycidae, (d) Sirex or (e) Trypodendron lineatum, (f) red streakiness, and (g) blue staining.

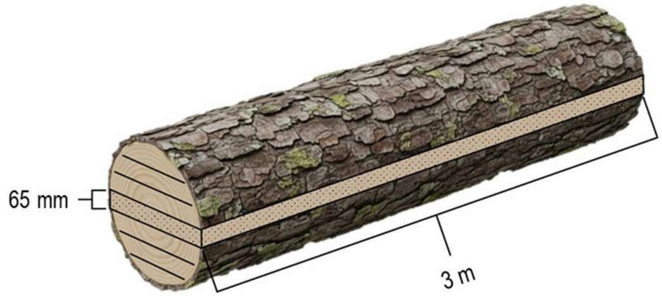

Figure 3. Sampling of 65 mm thick middle planks by a mobile band saw.

MCs of the different materials prior to and after the dry storage at a level of less than 0.05 ($p < 0.05$) significant difference.

2.5. Electrical resistance-based wood MC monitoring

The wood MC was monitored in dry storage piles ("Living", "Dead 0", "Dead 0.5") over a period of 30 months (February 2023–June 2025) to visualize the drying process of the logs. Three logs were selected per pile, and on each log, the following measuring equipment was installed. Dataloggers from Scanntronik Mugrauer GmbH (Zorneding, Germany) were used to record the electrical resistance (Gigamodul) and temperature (Thermofox universal). The electrical resistance was determined at two depths per log to show the differences between the heartwood at 80 mm and the sapwood at 20 mm. Stainless steel screws insulated with a shrinking tube were used as electrodes. To anchor the screw in the wood and measure the resistance at the appropriate depth, the tip of the screw (10 mm) remained uninsulated. At each measuring point, two electrodes were screwed at the centre of the log, at a distance of 30 mm from each other. To prevent electrical bridging, the holes were sealed with silicone at the edges (Figure 5).

The electrical resistance and temperature were recorded every 24 h, at 00:00. A regression function from Otten *et al.* (2017) was used to convert the electrical resistance into wood MC according to Equation (1).

$$MC = (a*T + b)*\exp(-c*R + d) + e \qquad (1)$$

where, MC: moisture content ([%]); *T:* temperature [°C]; *R:* electrical resistance [10logOhm]; *a:* −0.023569824; *b:* 2.443072848; *c:* 0.074072840; *d:* 6.825697870; *e:* 9.536085058.

3. Results and discussion

3.1. Change in roundwood quality during dry storage

The quality of the logs introduced into the dry storage piles varied depending on the state of the tree. Living trees, fresh

Table 3. Grading of sawn timber with respect to the occurrence of red streakiness and blue stain by a non-standardised method.

Grading	Occurrence [% area]
0	None
1	$x < 25\%$
2	$25 \leq x < 50\%$
3	$50 \leq x < 75\%$
4	$x \geq 75\%$

Figure 4. Sample design of gravimetric wood moisture content (MC) measurements on log sections prior and after dry storage. Red area marks the location of the heartwood test specimen and blue area marks the location of the sapwood test specimen.

logs respectively ("Living") were almost exclusively assigned to quality class B. Logs which originated from freshly dead trees ("Dead 0") and trees which were standing stored for 6 months ("Dead 0.5") showed noticeably lower quality. The class B percentage was only 15.4% and 29.4% respectively; 65.4% and 35.3% were assigned to class C, and the rest to class D, or even IW (Figure 6). After 30 months of dry storage, none of the logs were assigned to class B anymore; 58.8 to 71.9% were assigned to class C, 11.5 to 35.3% to class D, and 5.9 to 11.5% to class IW. The percentage of logs in class IW was even higher when secondary damage by wood-boring insects was taken into account in the evaluation, i.e. 21.9 to 69.2%. Insect damage was mainly caused by striped ambrosia beetles (*Trypodendron lineatum*), sawflies (*Sirex* spp.), and longhorn beetles (*Cerambycidae*). Although insect infestation led to a significant downgrading of roundwood quality when strictly following the assessment criteria according to RVR (Table 2), it must be added that in this study, the damage was limited to the outer portion of the logs (see also Figure 2). In addition to insect damage, the main causes of the decline in quality were rot, blue staining and red streakiness (Figure 7).

The percentage of logs with both red streakiness and fungal decay decreased with increasing SSD before dry storage, which could be explained by the initial wood MC of the logs. Fungal decay is limited by a lack of oxygen and water. Huckfeldt *et al.* (2005) suggested optimum MC between 35% and 70% for wood-destroying fungi. However, Brischke and Rapp (2008) demonstrated that significant decay can occur well below the optimal range. According to their research, fungal growth is possible even at a wood MC of 25%. Hence, the longer the snags stand in the forest, the more they dry and the lower is the risk of fungal infestation.

Künniger *et al.* (2023) observed red streakiness just a few months after bark beetle infestation. Michalec *et al.* (2024a) found early decay, already at the beginning of storage, while advanced decay was detected after a storage period of six months. Although our study did not distinguish between early and advanced decay, fungal degradation was observed in all three groups at the start of dry storage. In addition to the availability of water and oxygen, another risk of infection arises from damage to the bark and cambium, through which further basidiomycetes can infest the stem, initiate decay and

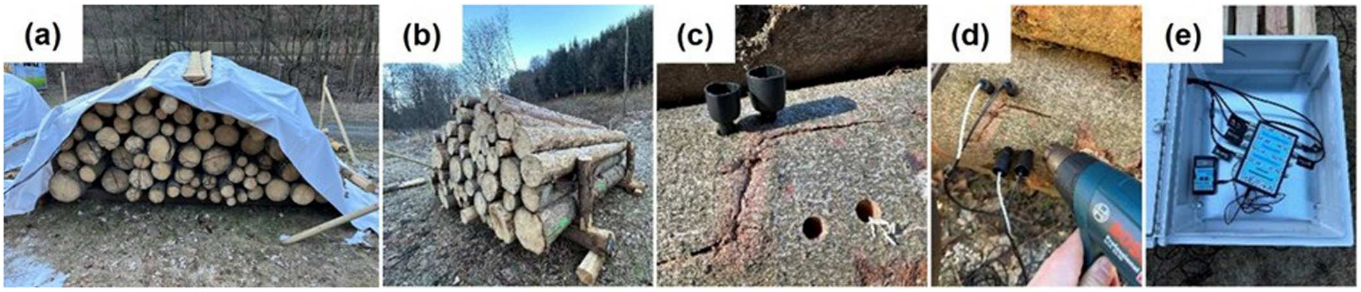

Figure 5. Set-up of the dry storage piles and installing measuring equipment. (a) Fully assembled dry storage pile with PVC-coated polyester fabric. (b) Construction of the dry storage facility with lateral posts and bedding posts to ensure clearance from the ground. (c) Drilled holes for installing the electrodes at a distance of 30 mm. (d) Heating up the shrinking tube and silicone application for isolating the electrodes. (e) Weatherproof box with measuring equipment (Gigamodul and Thermofox universal).

spread towards the inner heartwood (Rohmeder 1937, Kohnle 2015).

Blue staining also occurred before dry storage (Figure 7). Blue stain fungi, such as *Ophiostoma polonicum*, have a pronounced symbiotic relationship with the European spruce bark beetle. In this complex interaction, the fungus interrupts the transpiration flow of the tree, thereby creating a physiologically favourable environment for the development of beetle larvae (Furniss *et al*. 1990, Kržišnik *et al*. 2018). Consequently, primary infestation by *Ips typographus* in particular favours and promotes the subsequent development of blue stain in the wood. The rapid appearance of blue stain after bark beetle infestation has also been described by Künniger *et al*. (2023).

After 30 months of dry storage, 59.4% of the freshly stored logs, but only 1.5% of the logs taken from trees being dead for 0.5 years ("Dead 0.5") showed no signs of blue stain. At this time, the logs that had been stored standing for the longest time showed the highest risk of blue stain-induced discoloration because they were apparently moist enough during the entire period. Michalec *et al.* (2024a) observed an interesting phenomenon: at least visually, blue stain that was established in spruce wood was reduced after six months of storage. The authors attribute this to the leaching of mycelial pigments by precipitation as a result of severe drying or to an overlay of developing early decay. A similar decrease in blue stain was not observed in the present study.

During dry storage, MCs in the log sections decreased. Finally, after 30 months of storage, log sections showed MCs < 25%, which was observed independent of both the initial state of the log sections and heartwood as well as sapwood proportions (Figures 8 and 9).

Since the concept of calamity dry storage has not yet been adequately described in scientific literature, it is challenging to directly compare the present results with existing studies. Nevertheless, valuable parallels can be drawn with conventional wood storage, where round timber is usually stored in uncovered piles.

Regarding bark loss within a pile, Michalec *et al.* (2024b) reported that logs in the upper section layers lose the most bark due to direct and frequent moistening from precipitation. In contrast, the lower layers, which are protected from direct precipitation, remained permanently drier, which, in this case, correlated with significantly longer-lasting bark attachment. The observation of higher wood MC of logs in the upper layers of wood piles due to weather exposure is consistent with the study by Kofman and Kent (2009).

In addition to the position in the pile, Kofman and Kent (2009) also analysed the influence of coverage on the drying

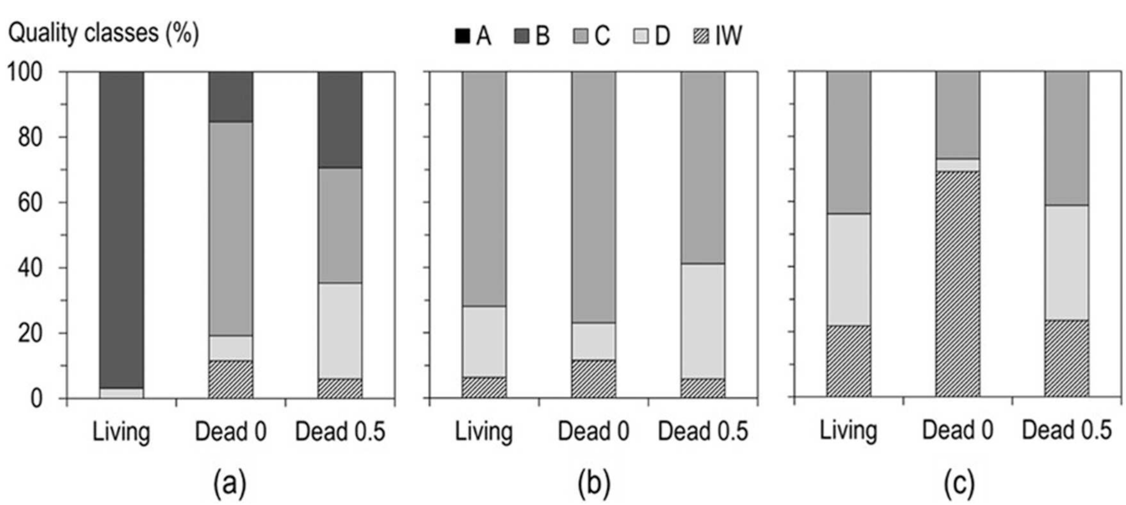

Figure 6. Percentage of quality classes before (a) and after 30 months dry storage without (b) and with consideration of damage by wood-boring insects (c) depending on the tree state at harvesting and beginning of the dry storage.

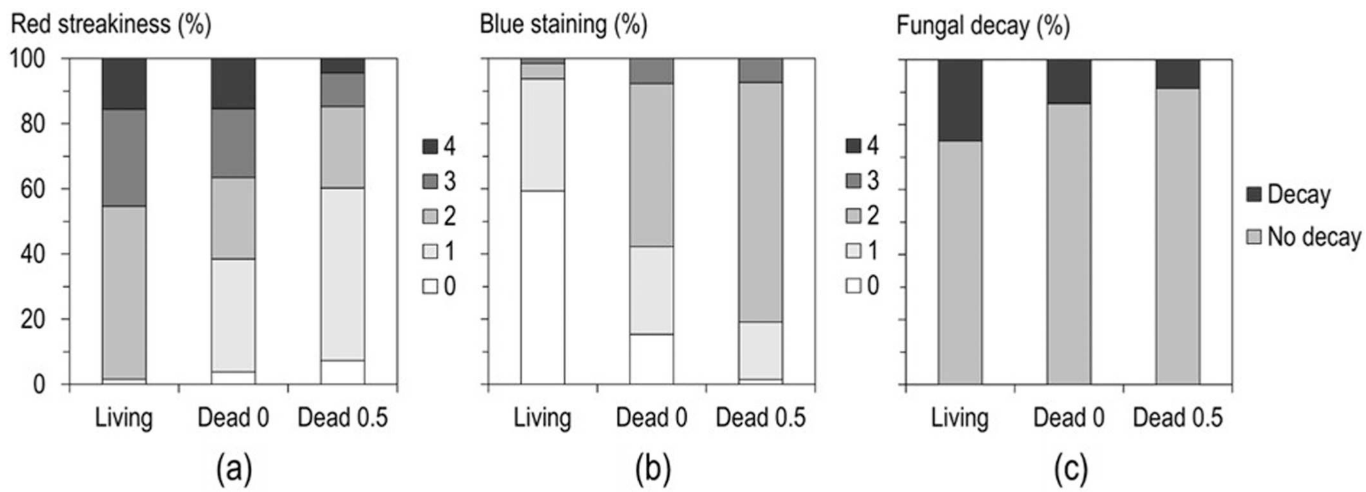

Figure 7. Percentage of logs affected by red streakiness (a), blue stain (b), and fungal decay (c) depending on the tree state at harvesting and beginning of the dry storage; Occurrence of the features "red streakiness" and "blue staining" on the surface area of middle planks: 0 = none, 1 = < 25%, 2 = 25 up to < 50%, 3 = 50 up to < 75%, 4 = ≥ 75%. Within-stem wood MC variation after dry storage.

process. They found that covering the piles improved drying in general and led to more homogeneity in the drying results across the entire pile. The logs in our study were taken from the top of the pile and should therefore not have a higher MC than the logs further down in the pile due to the cover, so that the moisture measurement of logs from the upper layer should be considered representative. Furthermore, their study investigates the time of starting the storage and the associated drying time. Accordingly, it takes around 22–24 weeks for the wood MC of fresh wood to fall from around 60% to below 30% if storage began in winter. With regard to drying under favourable conditions, Höldrich and Hartmann (2006) were able to show that wood felled and split in winter can achieve a wood MC of less than 20% within 9 months. Figure 9 shows that the "Living" trees in our study tended to be in the range of 30% MC only when measurements were taken after 19 months. However, when interpreting and transferring these reference values, it should be noted that the drying process is highly dependent on environmental conditions and wood dimensions. For example, Kofman and Kent (2009) only examined energy wood with significantly smaller diameters, whereas our study considered round wood with a diameter > 20 cm for potential high valuable usage.

3.2. Wood MC time series in dry stored snags

During dry storage, MC levels occur as a crucial storage criterion to prevent the deterioration of stored logs. By continuously measuring the electrical resistance in both the heartwood and sapwood of three logs per pile ("Living", "Dead 0" and "Dead 0.5"), the change in wood MC was determined and documented over a period of around 30 months. Figure 10 shows the average progression of MC measurements in the sapwood and heartwood for each pile.

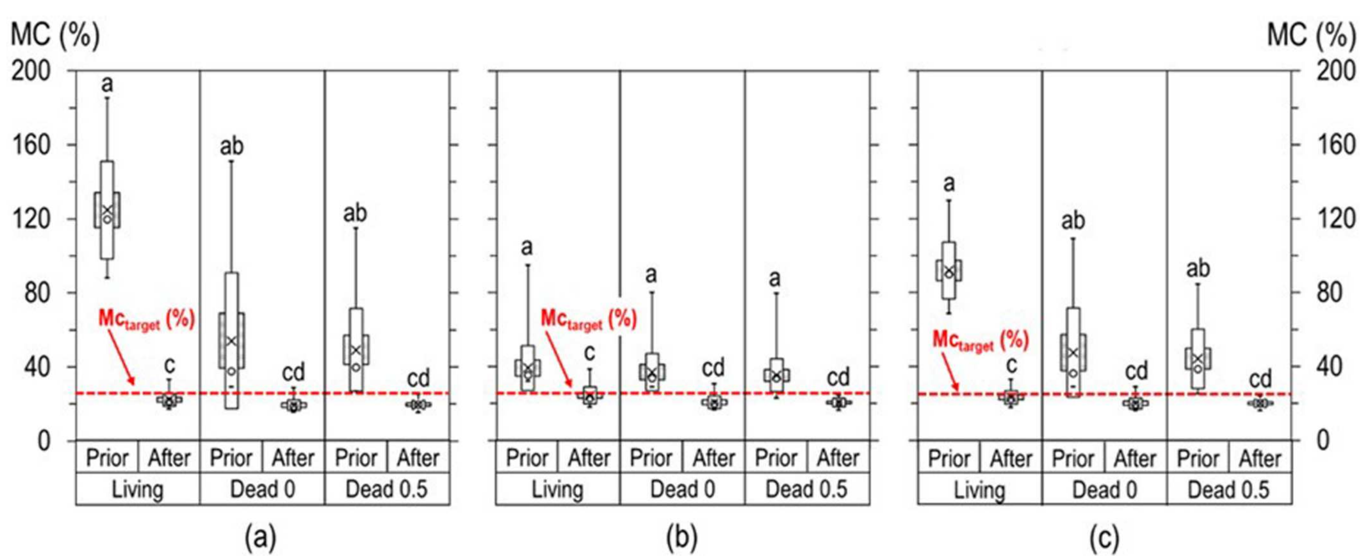

Figure 8. Wood moisture content (MC) measured gravimetrically in logs differentiated by sapwood (a), heartwood (b), and sap- and heartwood (c) sections prior to and after 30 months of dry storage depending on the tree state at harvesting and the beginning of the dry storage (Living, Dead 0 and Dead 0.5). Statistically significant differences related to the different tree states prior to and before dry storage are reported for a $p < 0.05$ level and labelled by differing letters.

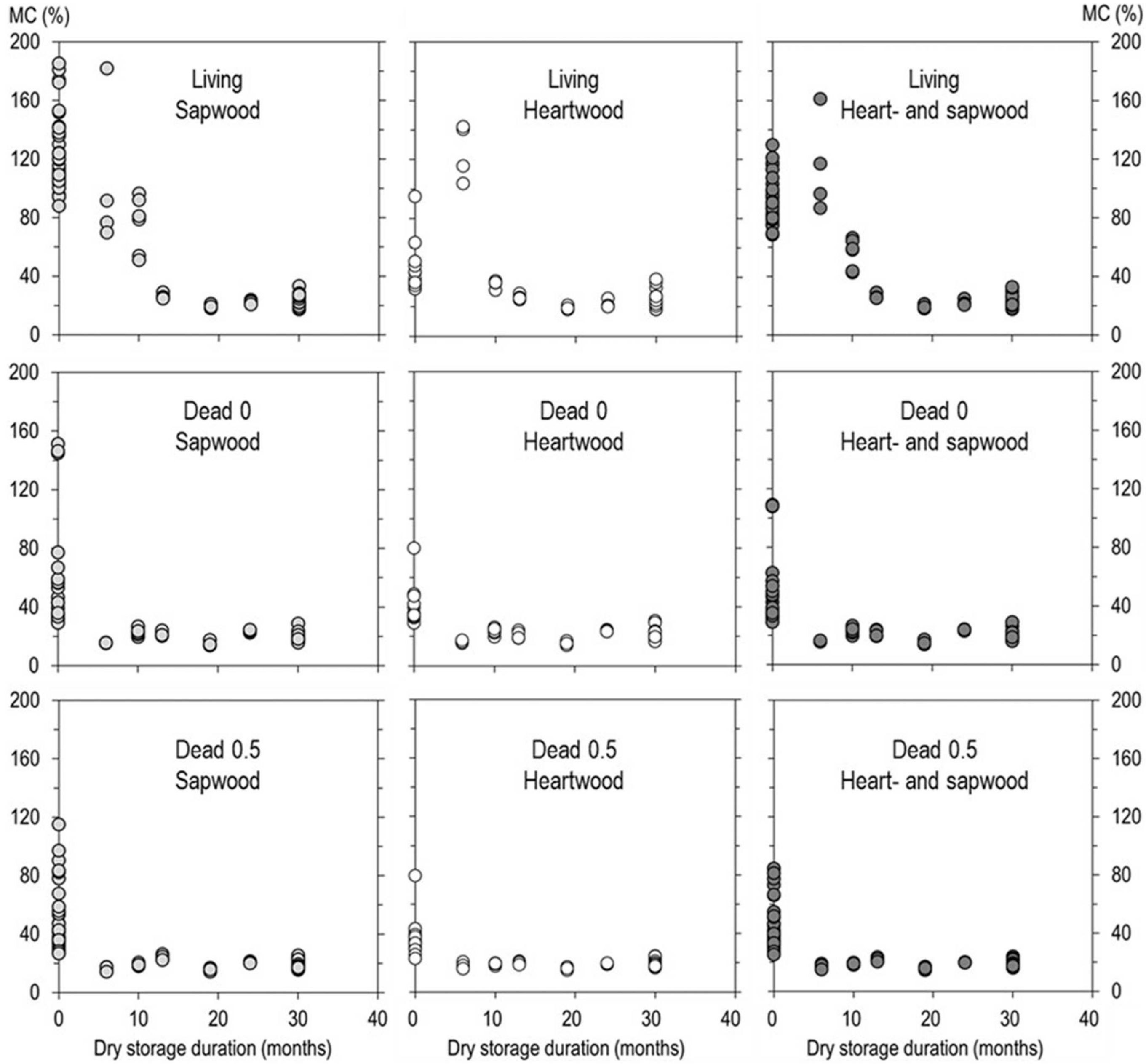

Figure 9. Wood moisture content (MC %, single values) development in logs during a 30 month dry storage depending on the tree state at harvesting and the beginning of the dry storage separated by sapwood and heartwood sections.

Standing-stored and pre-dried logs ("Dead 0" and "Dead 0.5") showed lower initial MC than wood that was still living before harvest. At the beginning of dry storage, the standing stored wood showed a rapid drying process, which led to a mean wood MC of under 25% in the sapwood after 3–4 months. The heartwood dried more slowly and took approximately 5–7 months to reach similar wood MC levels. During ongoing storage, the wood MC quickly reached 15%–20%. In comparison, the drying process of logs from living trees took considerably longer. While the sapwood started visibly drying in April 2024 after more than a year of storage, the drying process of the heartwood only began to dry significantly in September 2024. By the time the logs were removed after approximately 2.5 years in June 2025, the sapwood had reached an MC of less than 20%, whereas the heartwood remained at a level of around 25%. An MC below this critical level of 25% is reached much earlier by spruce wood that has been stored standing, as opposed to that of living trees in dry storage (Brischke and Rapp 2008). It should be noted that even at the end of the storage period, heartwood was still at the MC limit for fungal degradation, which meant that there was a permanent risk of deterioration. Because the sapwood in the logs of all three piles dried out faster on average and reached MCs below 25%, there was a risk of deterioration of the heartwood over a longer period.

In December 2023, a sharp increase in wood MC was recorded in the "Dead 0.5" pile. This was because the tarpaulin cover was loosened by the wind, leaving the pile partially uncovered for several weeks. During this period, precipitation, including snow, caused the wood to become moist. After the

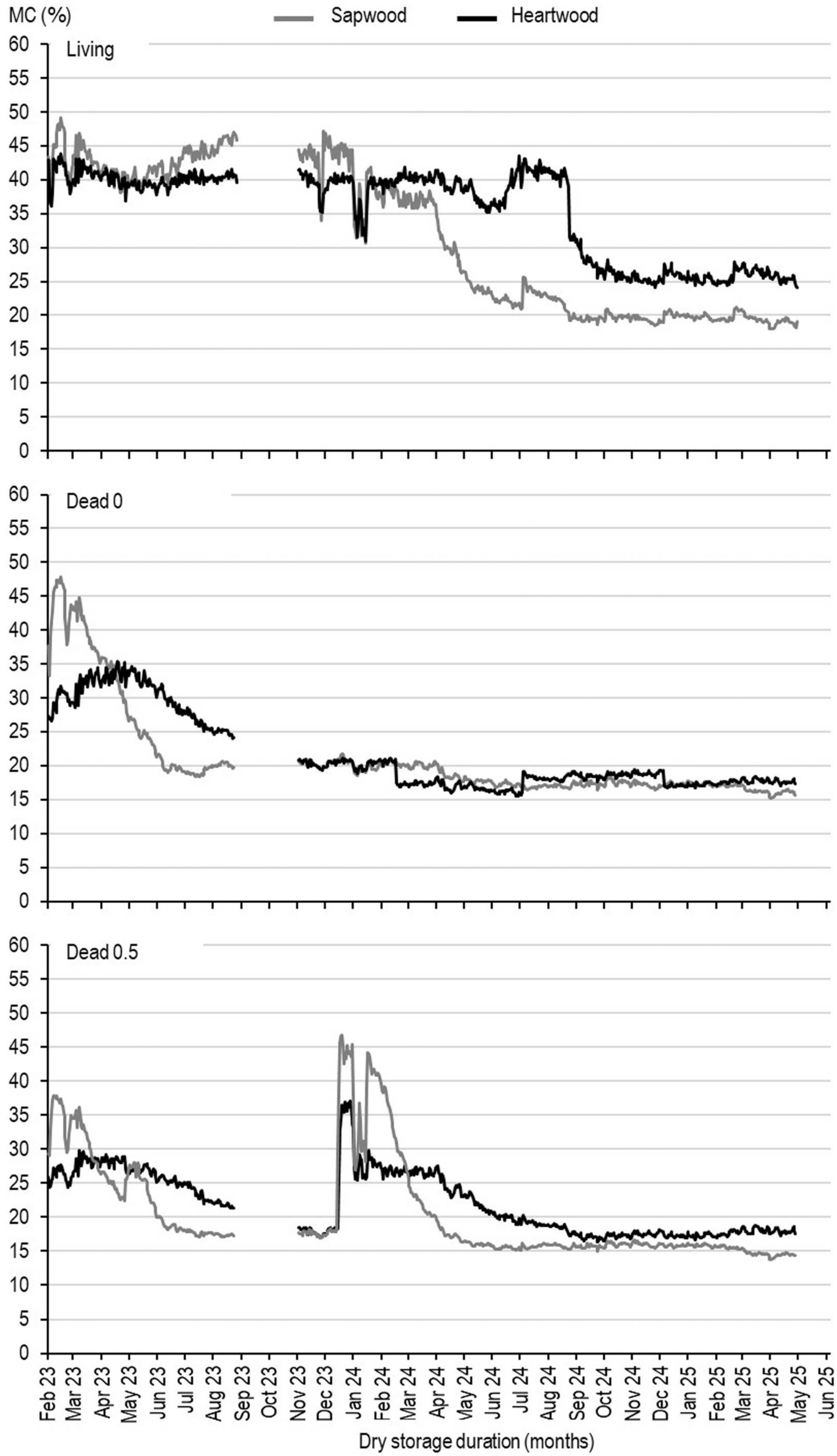

Figure 10. Mean wood moisture content (MC) out of three measurements in the heart- and sapwood of logs in dry storage piles “Living”, “Dead 0”, “Dead 0.5”. Determination based on electrical resistance measurements and corresponding air temperature (Period: 09 February 2023–2011 June 2025).

pile was repaired, the drying process resumed in the sapwood and heartwood. Sudden drops in wood MC when the temperature is below 0°C can be explained by the formation of ice crystals, which hinder ion transport (Yue *et al.* 2018). The higher electrical resistance of the frozen water is represented as lower wood MC in the corresponding curves. It is obvious that the effect is more pronounced the higher the wood MC is, or rather, the more free water is present in the cells that can freeze. Thus, the decline in wood MC is most prominent at "Dead 0.5", whereas it is barely noticeable at "Dead 0". A frost period between February 2025 and March 2025 did not cause any dips in the curves, as advanced drying took place under cell wall saturation.

A comparison with the results of gravimetric wood MC determination prior to storage showed that the wood MC in the sapwood of living trees, which averaged 124.8 ±&plusmn26.4%, could not be mapped clearly in the results of the electrical resistance measurements. In general, the measurement of electrical resistance loses precision as soon as free water is present in the wooden cells. Another reason for the differences between the two measurement methods may be that different logs and zones within the logs were measured. Larsen *et al.* (2011) described differences in wood MC along the cross-section due to the physiological differences between heart- and sapwood. Trendelenburg and Mayer-Wegelin (1955) found significant moisture differences inside freshly harvested logs, which became even more pronounced during storage in the forest. It is possible that such small-scale moisture differences occur both during standing storage and afterwards in the dry storage.

With regard to maintaining the quality of logs in dry storage, measuring wood MC levels well above cell wall saturation plays a minor role anyway, as cell wall saturation also represents a limit above which fungal degradation may occur. Provided that wood moisture levels below cell wall saturation can be reliably determined, it is possible to determine the point at which fungal infestation is limited and the risk of decay in dry stored logs decreases.

4. Conclusions

Dry storage offers a simple, less elaborate and cost-effective conservation technique for standing-stored and thus pre-dried beetle-infested calamity timber. Secondary infestation with insects occurred, but was limited to the outer stem zones. Standing-stored wood is characterised by a lower initial MC and faster drying in dry storage compared to wood that was still alive. Thus, prolonged standing time may have beneficial effects. Damage to the pile, especially within the tarpaulin cover, must be avoided to prevent interruption of the drying process and to reduce the risk of depreciation.

Further studies are needed to (1) verify the impact of the initial MC-levels on the final roundwood quality as elevated MCs may facilitate the infestation and decay by wood-destroying fungi, (2) identify viable storage periods (> 2.5 years) and (3) assess the need for monitoring to reduce the risk of quality deterioration during wood storage. Finally, and for this reason, full-scale piles were assembled as "best-practices" based on the state of the art in August 2025 in order to evaluate and validate the findings of this study.

Acknowledgements

The authors sincerely thank the valuable input provided by the partners of the NUKAFI project, in particular, Marcus Schwartz, for his support during the assembly and monitoring of the dry storage piles. Further thanks go to the Dipl. Geographers Julian Pape and Meinolf Pape from Wetterportal Pape Gbr who provided the weather data from a local weather station. C.B., J.F.T., H.F., and L.E. acquired, analysed and interpreted the data. All authors drafted and revised the manuscript. The conception of the study and the design of the experiments was done by H.M., S.W., C.B., J.F.T., and L.E., H.M., S.W., C.B., and L.E. supervised the study.

Author contributions

CRediT: **Jan-Frederik Trautwein:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing; **Lukas Emmerich:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing; **Hannes Fritsching:** Data curation, Formal analysis, Investigation, Resources, Validation, Writing – original draft; **Holger Militz:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing; **Stefanie Wieland:** Conceptualization, Funding acquisition, Project administration, Supervision, Validation, Writing – review & editing; **Christian Brischke:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research was funded by the German Federal Ministry of Food, Agriculture, and Regional Identity (BMLEH) and the German Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety (BMUKN) via the Agency for Renewable Resources (FNR) [grant number 2220WK49E3].

References

Becker, L., 2022. *Erdlagerung von Fichtenkalamitätsholz: Untersuchungen zur Holzfeuchte und zu Anteilen von Verfärbungen und Fäule*. Bachelorarbeit: Technische Universität Dresden, Professur für Forstnutzung, Dresden.

BMEL, 2024. Massive Schäden – Einsatz für Wälder und Waldumbau nötig. Available from: https://www.bmel.de/DE/themen/wald/wald-in-deutschland/wald-trockenheit-klimawandel.html [Accessed 26 June 2026, 16:18].

Brischke, C., *et al.*, 2021. Foil storage for conservation of beetle-infested spruce logs – a feasibility study. *Pro Ligno*, 17, 11–17.

Brischke, C., *et al.*, 2024. Schutz von lagerndem Rundholz – Verfahren, Wirksamkeit von Schutzmaßnahmen und Qualitätseinbußen. 32. Deutsche Holzschutztagung, Dresden, 25–26 April 2024. 34–56.

Brischke, C., and Rapp, A.O., 2008. Dose–response relationships between wood moisture content, wood temperature and fungal decay determined for 23 European field test sites. *Wood Science and Technology*, 42, 507–518.

Bücking, M., Eisenbarth, E., and Jochum, M., 1997. *Untersuchungen zur Lebendlagerung von Sturmwurfholz der Baumarten Fichte, Kiefer, Douglasie und Eiche*. Mitteilungen aus der Forstlichen Versuchsanstalt Rheinland-Pfalz, No. 42/97.

Emmerich, L., *et al.*, 2025. Developing calamity management strategies: dry and foil storage of bark beetle-infested spruce logs. Scientific poster. Innovawood General Assembly 2025, Kastoria, Greece.

EN 13183, 2002. *Moisture content of a piece of sawn timber – part 1: determination by oven dry method*. Brussels: CEN European Committee for Standardization.

EN 252, 2015. *Wood preservatives. Field test methods for determining the relative protective effectiveness in ground contact*. Brussels: CEN European Committee for Standardization.

Furniss, M.M., Solheim, H., and Christiansen, E., 1990. Transmission of blue-stain fungi by Ips typographus (Coleoptera: Scolytidae) in Norway spruce. *Annals of the Entomological Society of America*, 83 (4), 712–716. doi:10.1093/aesa/83.4.712.

Höldrich, A., and Hartmann, H., 2006, *Meist reicht ein Sommer -Lagerung und Trocknungsverlauf von Scheitholz intensiv untersucht* . Bayer. Landwirtschaftliches Wochenblatt Nr. 13.

Huckfeldt, T., Schmidt, O., and Quader, H., 2005. Ökologische Untersuchungen am Echten Hausschwamm und weiteren Holzfäulepilzen. *Holz Roh-Werkst*, 63, 209–219.

Hýsek, Š., Löwe, R., and Turčáni, M., 2021. What happens to wood after a tree is attacked by a bark beetle? *Forests*, 12 (9), 1163.

Jonsson, M., 2004. *Wet storage of roundwood – effects on wood properties and treatment of run-off water*. Doctoral dissertation. Swedish University of Agricultural Sciences SLU, Uppsala.

Jonsson, M., 2007. Live storage of *Picea abies* in Sweden after storm felling. *Scandinavian Journal of Forest Research*, 22, 344–350.

Jonsson, M., 2012. Dry and wet storage of *Picea abies* and *Pinus contorta* roundwood with and without bark. *Wood Material Science and Engineering*, 7, 41–48.

Kofman, P.D. and Kent, T., 2009. Long term storage and seasoning of conifer energy wood. *Consulted Apr*, 12, 2015.

Kohnle, U., 2015. Gegen Rotfäule kann man etwas tun. *Badische Bauern Zeitung*, 11, 30–31.

Kržišnik, D., *et al*., 2018. Performance of bark beetle damaged Norway spruce wood against water and fungal decay. *BioResources*, 13 (2), 3473–3486.

Künniger, T., Elsener, R., Heeb, M., and Huch, A., 2023. Mechanical properties of Norway spruce (*Picea abies*) infested by the bark beetle (*Ips typographus*). *Wood Material Science & Engineering*, 19 (1), 85–91. doi:10.1080/17480272.2023.2226644.

Larsen, F., Ormarsson, S., and Olesen, J.F., 2011. Moisture-driven fracture in solid wood. *Wood Material Science and Engineering*, 6 (1–2), 49–57. doi:10.1080/17480272.2010.532234.

Michalec, K., *et al*., 2024a. Dynamics of wood decay in the cross-section of logs as a result of long-term storage in a landing yard. *Drewno. Prace Naukowe. Doniesienia. Komunikaty*, 67 (214), 00030. doi:10.53502/wood-192478.

Michalec, K., *et al*., 2024b. 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. *Sylwan*, 168 (1), 19–32. doi:10.26202/sylwan.2023102.

MLV NRW, 2024. Waldzustandsbericht 2024 – Bericht über den ökologischen Zustand des Waldes in Nordrhein-Westfalen – Kurzfassung. November 2024.

Niesar, M., *et al*., 2018. Fichten-Borkenkäfer-Massenvermehrung in nie dagewesener Intensität. Available from: http://www.waldwissen.net [Accessed 26 June 2026, 16:00].

Otten, K.A., Brischke, C., and Meyer, C., 2017. Material moisture content of wood and cement mortars–electrical resistance-based measurements in the high ohmic range. *Construction and Building Materials*, 153, 640–646.

Persson, E., and Elowson, T., 2001. Moisture content and discoloration of wood during dry and wet storage of Norway spruce (*Picea abies* (L.) Karst.) pulpwood. *Paperi ja Puu/Paper and Timber*, 83, 132–137.

Plattform Forst & Holz, 2024. Rahmenvereinbarung für den Rohholzhandel in Deutschland (RVR). 6th ed.

Rohmeder, E., 1937. *Die Stammfäule (Wurzelfäule und Wundfäule) der Fichtenbestockung*. Mitteilungen der Bayer. Staatsforstverwaltung 23.

Trautwein, J.-F., *et al*., 2025a. Protection of stored roundwood: methods, efficacy of protective measures, and quality losses. *Discover Forests*, 1 (1), 1–16.

Trautwein, J.-F., *et al*., 2025b. Outer appearance of bark-beetle-infested stands of Norway spruce after different standing storage durations: a case study in the Harz Mountains, Germany. *Journal of Forestry Research*, 36, 1–17.

Trendelenburg, R., and Mayer-Wegelin, H., 1955. *Das Holz als Rohstoff*. Munich: Carl Hanser Verlag.

Yue, X., *et al*., 2018. Investigations on the effects of seasonal temperature changes on the electrical resistance of living trees. *Forests*, 9 (9), 550.