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REVIEW

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Protection of stored roundwood: methods, efficacy of protective measures, and quality losses

Jan-Frederik Trautwein[1*], Holger Militz[1], Nicole Starke[2], Björn Günther[3], Armin Meurer[4] and Christian Brischke[5]

*Correspondence:
Jan-Frederik Trautwein
jan-frederik.trautwein@uni-goettingen.de
[1]Faculty of Forest Sciences and Ecology, University of Göttingen, Wood Biology and Wood Products, Buesgenweg 4, 37077 Goettingen, Germany
[2]Institute of Forest Utilization and Technology, Dresden University of Technology, Pienner Str. 19, 01737 Tharandt, Germany
[3]Institute of Soil Science and Site Ecology, Dresden University of Technology, Pienner Str. 19, 01737 Tharandt, Germany
[4]Faculty of Resource Management, HAWK University of Applied Sciences and Arts – Hildesheim/Holzminden/Goettingen, Buesgenweg 1a, 37077 Goettingen, Germany
[5]Thünen Institute of Wood Research, Leuschnerstr. 91d, 21031 Hamburg, Germany

Abstract
The forestry and timber industry is increasingly confronted with large quantities of calamity round wood, which must be stored for longer periods of time and needs to be protected from losses of quality. This review provides an overview of today's and potential future storage methods. Results from German recently completed and ongoing research projects on storage of round wood under foil, in-ground, dry and standing storage are presented and the different methods are evaluated against the background of the current framework conditions. Wet storage allows several years of conservation, but is not sustainable due to the decreasing availability of water and soil contamination due to washouts. Foil storage using the "Baden-Württemberg method" is more reliable but also more expensive than the "Swiss method" due to the complete exclusion of oxygen. Both methods have limitations with respect to the storage of logs from beetle infested trees. Earth storage is a new approach with successful oxygen reduction, but further research regarding the wood moisture is required. Leaving dead trees in the forest on stock, so called "standing storage" preserves wood by drying, but there is currently a lack of scientific findings. Live storage, in which the root ball of thrown trees remains on the trunk, preserves the wood quality over a vegetation period. "Calamity wood dry storage", a special form of dry storage, is used for storage of bark beetle infested Norway spruce from months up to years.

Keywords Wet storage, Foil storage, In-ground storage, Standing storage, Live storage, Dry storage

1 Introduction

The accumulation of climate change-related weather events has led to an enormous amount of calamity wood in Germany and some neighbouring countries in recent years [25]. In addition to large quantities of storm-damaged timber as a result of hurricane Friederike (January 2018) and several storm depressions in January/February 2022, large damaged areas were recorded due to infestation with bark-breeding beetles, particularly in Norway spruce (*Picea abies* [L.] Karst.) stands. The calamities were accelerated by the pronounced summer droughts in 2018, 2019, 2020 and 2022, which resulted in enormous amounts of calamity wood in central Europe. From 2018 to 2023, around 135 mio. m^3 of calamity wood was harvested in the Czech Republic, around 53 mio m^3 in Austria and around 272 mio. m^3 in Germany [12, 36, 37].

Driven by the calamity, the total wood harvest in Germany peaked in 2021 with around 83 mio. m^3. In this year, Norway spruce accounted for around 75% (62 mio. m^3) of the harvested wood, while the volume for European beech (*Fagus sylvatica* L.) was 9 mio. m^3 [6]. At times, these large amounts of calamity wood led to massive bottlenecks in harvesting, transport and storage and caused considerable disruption to the timber market. In particular, the difficult timber market situation in 2018 made it necessary to store large amounts of roundwood in the forest or close to the forest, sometimes for several years [27, 28, 33, 59, 65]. The method of wet storage by sprinkling, which has been established for many decades, could not be used in many places due to the prevailing water shortage [52, 69]. Newer methods, such as foil storage developed in the 1990s, experienced a renaissance as a result [16, 29]. Out of necessity, dry storage facilities were also created or the wood was left, stored standing in the forest.

The question of the most suitable method for the mid to long-term storage of calamity wood cannot be answered in general terms. The suitability of the process depends on the source material, logistical issues and the boundary conditions (available space, water availability, rules and regulations, etc.) as well as the market situation. While storm leads to large quantities of damaged timber at once, which can then be harvested fresh and usually lying down, bark beetle infested wood is produced gradually and dries out relatively quick until it is finally harvested standing upright [3, 20, 28]. The situation is similar with trees that have died due to drought stress. Calamity wood therefore differs greatly in terms of the degree of vitality, the harvesting conditions, previous mechanical damage and the general wood quality. The latter can also vary greatly in a small area, which may require small-scale adaptation of the harvesting and storage processes to the respective conditions on site or in a decentralised manner. In general, however, calamity wood is harvested in larger quantities in a smaller area than regularly harvested wood, is not predictable in terms of time and is of lower quality. It is also damaged by breakage, beetle infestation, blue stain and rot, as well as harvest and transport damage.

Depending on the parameters mentioned above, there are different uses for calamity wood, ranging from the production of sawn timber for the construction sector, to the production of wood-based panels and pulp, with notable differences in achievable selling prices. Therefore, the decision as to whether round timber can and should be stored after a calamity, and for how long, depends on a number of factors. This review aims at providing an overview of the methods currently used for the medium and long-term storage of round timber and the associated protection of the wood. Current German studies, in particular on the special features of storing beetle wood, will be presented, as well as new approaches that have emerged in the wake of the current calamity.

2 Methods of roundwood storage

2.1 General aspects

After felling and transportation, the logs are usually stored before they are further processed for the production of sawn timber, wood-based materials or pulp. This storage is usually short-term (several days to a few weeks) and takes place in log piles in the forest and/or in the log yard of the processing companies. Longer-term storage of logs (several months to a few years) may become necessary after unplanned harvesting due to calamities, as transport and processing capacities are exhausted. As a consequence, there is a shortage of storage space in the forest or at the companies and additional storage areas need to be created. In order to protect the wood from secondary damage caused by fungal or insect infestation, it is necessary to create unfavourable conditions for decay organisms. This can be achieved in various ways by controlling the availability of air and water [2, 10, 30, 42]. The use of biocides is severely restricted in the forest and should always be a last resort—biocide-free methods are favoured [3, 17].

Table 1 provides an overview of biocide-free methods for the long-term storage of roundwood, whereby three principle modes of protective action can be distinguished:

- Lowering the wood moisture below cell wall saturation (formerly: fibre saturation); < 20 – 30% wood moisture content.
- Lowering the oxygen content
- Maintaining the vitality of the tree

Other than the storage methods mentioned above, the transport of logs with bark in standardised containers, especially over long overseas routes by ship, requires a special form of log preservation. In addition to preserving quality, the focus here is on the phytosanitary treatment of the wood to prevent wood pests from being introduced into the destination country with the logs.

2.2 Wet storage

Logs are stored wet either by sprinkling or by immersion in water. The latter, however, has more historical significance, playing a role primarily in connection with the transport of logs by rafting. However, both methods aim to adjust the moisture content of the wood so that the oxygen (O_2) content is too low for the respiration of wood-colonising fungi [15, 32, 44]. The targeted wood moisture content is above 150%. In this range, the risk of infestation by fungi and insects is very low due to a lack of oxygen [63]. Nevertheless, colonisation by bacterial species is at least possible under these conditions [5, 14].

Sprinkling is considered a reliable and established storage method for roundwood and has developed into the most important method for the long-term storage of storm-felled timber in the 1960s and 1970s [43, 69]. As a rule, bark attached roundwood is stored on large piles in the forest, near the forest, or in the sawmill by continuous or periodic sprinkling of the mantle and cross sections of the logs. The irrigation of debarked wood is rather uncommon [21]. The washout of bark extractives can lead to tannin

Table 1 Methods of roundwood storage

Method		Bark	Mode of action	Protection against
Wet storage	Water storage	On	Reduce oxygen	Fungi, insects
	Sprinkling	On	Reduce oxygen	Fungi, insects
Foil storage	Swiss method	On	Increase moisture	Fungi, insects
	Baden-Württemberg method	On	Reduce oxygen	Fungi, insects
In-ground storage		On	Reduce oxygen	Fungi, insects
Standing storage (snag)		On	Reduce moisture	Fungi
Live storage (Storm wood with root plate)		On	Maintain vitality	Fungi, insects
Dry storage	Without cover	Off	Reduce moisture	Fungi, insects
		On	Maintain moisture	Fungi
	With cover	On/Off	Reduce moisture	Fungi

discolouration and leaching of the wood [21, 24]. However, insufficient irrigation bears a risk of blue stain colonisation [46]. The irrigation intensity should therefore be adjusted so that the wood moisture content is always sufficiently high, but leaching from the wood and bark is minimised in order to maintain the wood quality, reduce uneccesary water consumption and to minimise pollution of the groundwater. A particular difficulty with regard to controlling the irrigation intensity arises from the variability of the initial moisture content of the stored log sections [55]. Storage periods of several years are possible without serious loss of quality of the irrigated logs [1, 57]. In the winter months, there is a risk that sprinkler systems are damaged by frost and that the wood is no longer sufficiently moistened, especially when warm and cold periods are alternating.

With regard to infestation by harmful organisms, it has been shown that the irrigation of roundwood can supress the infestation of the European spruce bark beetle (*Ips typographus* L.), but it cannot completely prevent it [48]. Characteristics that irrigated wood can exhibit after long-term storage are infestations with the honey fungus (*Armillaria mellea* [Vahl] P. Kumm), mould or bacteria [69]. The latter can lead to inhomogenous permeability and thus liquid uptake, for instance of coating materials or wood preservatives, due to the partial degradation of pit membranes in the tracheid cell walls.

A prerequisite for the operation of sprinklered wet storage facilities is a sufficient amount of water, which has not been available in many places in Germany over the past years. Existing wet storage facilities have already had to be drained in the past due to drought [41]. With regard to the construction of new wet storage facilities and the associated search for locations, sufficient water availability as well as water and nature conservation must be guaranteed. In addition, complex and complicated authorisation procedures need to be followed. One possible alternative would be the use of a wet storage facility in a recirculation system [64].

2.3 Foil storage

The massive occurrence of storm and bark beetle damage combined with the water shortage over the past years has brought foil storage back into focus, which was already developed and extensively investigated in the 1990s [10, 34, 38, 39, 58].

There are two different methods of foil storage. According to the "Baden-Württemberg method", wood piles are completely enclosed in foil and thus packed airtight, whereas piles created using the "Swiss method" are open to the ground so that soil moisture can get into the foil tent but cannot release upwards (see Table 1). Numerous studies have shown that the “Baden-Württemberg method” has a significantly higher protective effect than the Swiss method [18, 49–51, 62], since fungal growth and wood decomposition can only be prevented if the wood is completely sealed off from the ambient air. Nevertheless, both methods are still used today.

A prerequisite for reducing the oxygen (O_2) content in the foil tent is the presence of living cells that respire the residual oxygen. This can be done by microorganisms or living cells in the wood [35]. Studies with miniature piles showed that severely damaged bark beetle infested wood is not able to sufficiently reduce the O_2 content in a foil tent to prevent fungal activity [7]. In miniature piles designed according to the “Swiss method”, the O_2 content was not reduced using either bark beetle infested wood or vital spruce wood. Only the storage of Norway spruce infested with bark beetles and still needled according to the “Baden-Württemberg method”, led to an atmosphere within the foil pile that suppressed further fungal growth and significantly reduced the decomposition of the wood (Fig. 1).

Methods for foil storage of roundwood were developed in the aftermath of the hurricanes Vivian and Wiebke in 1990. Freshly felled wood is rich in still-living parenchyma cells, which consume the residual oxygen in a foil pile and reduce it to such an extent that it is not sufficient for the respiration of wood-destroying fungi. To ensure that the O_2 content in the pile remains permanently low, the foil tent must remain tightly sealed. This requires a series of sometimes complex measures. Storage areas must be levelled and cleared of sharp-edged objects, water drainage must be ensured, mouse protection fabric must be applied and timber cut edges must be rounded off. The work involved in preparing a foil storage facility is therefore not insignificant. In addition, even after the storage facility has been set up, the piles must be monitored continuously and checked regularly for leaks. This monitoring is usually done manually by measuring the O_2 or carbon dioxide (CO_2) content.

Long-term experience with wood stored wrapped in foil according to the "Baden-Württemberg method" is limited and the long-term change in the atmosphere in foil piles has only been comprehensively documented in a few cases.

As part of a case study, 32 foil piles of Norway spruce which were created after the Friederike storm in 2018, were monitored in the forest district of Dassel (Lower Saxony State Forests, Germany). Within this study the conditions for wood-destroying fungi on the basis of the O_2 and CO_2 levels in the piles were monitored and the resulting wood quality was evaluated [8].

All the analysed piles showed a similar progression. The O_2 concentration dropped to almost 0% within a few days, while the CO_2 content increased over months, reaching maximum values between 27 and 56% and then dropping to between 12 and 25%. Temperature-related fluctuations in the CO_2 content were caused by the activity of microorganisms, particularly in the first year of storage. As the storage period increased, this effect decreased due to the lack of oxygen and the death of the organisms. Damage to the foil led to an increase in O_2 and a delayed increase in CO_2 due to reactivated microorganisms.

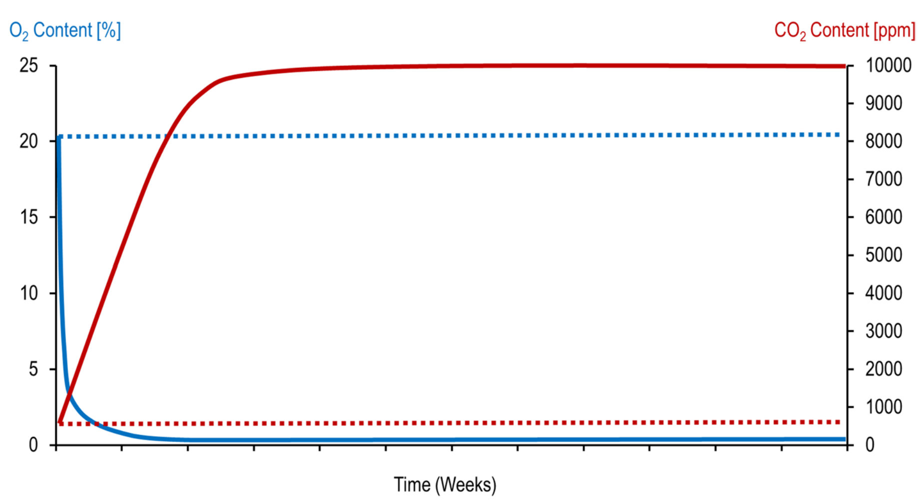

Fig. 1 Schematic illustration of the oxygen (O_2) and carbon dioxide (CO_2) content within the foil-pile in different concepts of foil storage (Baden-Württemberg method = solid lines; Swiss method = dotted lines) based on the study by [7] on the effectiveness of foil storage of beetle infested Norway spruce

The atmosphere within the piles varied in terms of its suitability for the growth of microorganisms, which led to different degrees of risk to the wood. In extreme cases, piles had to be broken up prematurely due to an uncontrollable rise in O_2 as a result of severe damage (Fig. 2).

The findings of the monitoring study over a period of 3.5 years can be summarised as follows:

Around one third of the foil piles needed to get dissolved prematurely due to various types of damage, while others were dissolved for timber sales. In only four of 32 piles, the O_2 content was close to 0% until the end of the measurement period or until the piles were dissolved, with two of these piles being dissolved after less than two years. The evaluation of the wood quality on the basis of two prematurely dissolved piles showed that only 30% of the sampled material was not downgraded to RVR quality class D.

The Framework Agreement for the Round Wood Trade in Germany (RVR) represents a sorting guideline for round wood and aims to ensure standardised, transparent and clearly defined usage for round wood trade in Germany [53].

However, the presence of rot visible on the cross-section was the decisive factor for a drop in quality. By cutting off the infected parts the majority of the log would still have been assigned to RVR-quality B/C, as the rot had only spread a few centimetres from the end-grain. In general, the results confirmed that once damage to the foil has occurred, there is little time for opening the pile and further processing the logs, if further rot damage shall be avoided. However, with appropriate care, an early begin of storage, fast processing, transporting and sealing, immediate repair of leaks and high-frequency monitoring, the investment in foil storage can certainly lead to a positive result.

Various storage methods for poplar (*Populus nigra* L.) logs from short-rotation coppice were investigated at the Dresden University of Technology, including foil storage for 21 and 48 months. In the latter, ten small foil piles (1.4 m^3) of logs with and without bark were analysed. Within about three weeks, an oxygen-free atmosphere developed in almost all of the piles, accompanied by an increase in CO_2 concentration, which reached maximum values of 27% to 35% after 7 to 16 weeks. In the further course, the CO_2-concentration decreased and was 6%—13%, 5%—10% and 5%—12% after 9, 21 and 48 months, respectively.

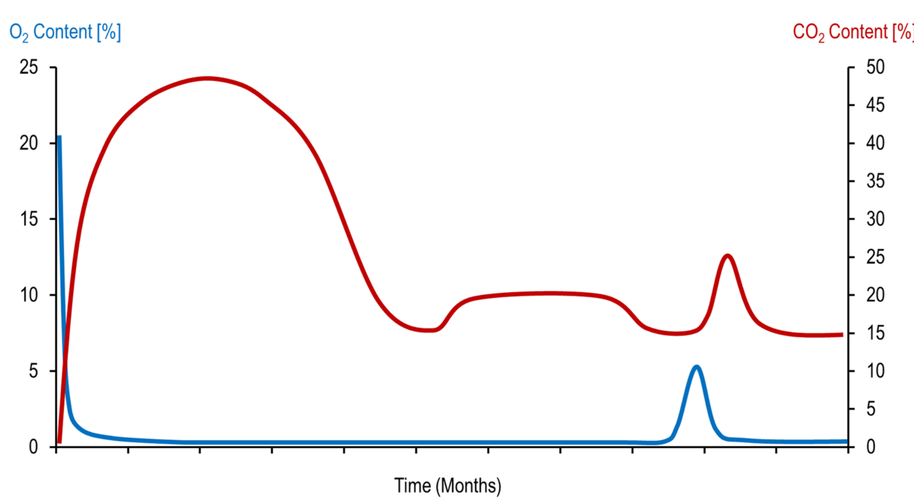

Fig. 2 Schematic illustration of the oxygen (O_2) and carbon dioxide (CO_2) content within the foil-pile (Baden-Württemberg method) based on the study of [8]

The study also showed that damage to the foil, caused by mice or leaking weld seams, causes that an oxygen free atmosphere cannot be achieved. Figure 3 illustrates an example of how the CO_2 and O_2 concentration developed during the foil storage.

High wood moisture contents were maintained using all foil storage variants (9 months: 158%, 21 months: 151%, 48 months: 149%). The wood quality of the poplar logs was largely maintained, assessed on the basis of the oven-dry density and chemical composition (9 and 21 months). Significant density reductions occurred in only one variant. Neither rot nor wood-destroying fungi were detected either macroscopically or microscopically. However, typical bacterial infestation and superficial, white(ish) fungal mycelium occurred (Fig. 4) [19, 60].

Due to the fact that the wood came from short-rotation coppice and the diameters were therefore small, it is questionable to what extent the results shown can be transferred to round wood with bigger diameters, including other types of wood. However, results from foil-storage tests using the "Baden-Württemberg method" with bark beetle infested Norway spruce wood also show positive results after several years of storage [40, 68].

2.4 In-ground storage

An O_2-seal can also be achieved by enclosing round timber with a soil substrate [70]. Initial practical experience with this type of in-ground storage of storm-felleded timber was gained in Switzerland in the aftermath of Hurricane Lothar in 1999 [67]. After a storage period of 2.5 years, the Norway spruce and silver fir (*Abies alba* Mill.) timber was of an unaltered high quality. The only downside was that the covering of soil particles increased tool wear during subsequent cutting.

In-ground storage is still a largely unexplored conservation method, as no further results have been published apart from the Swiss trial described above. Against the backdrop of the large quantities of calamity wood that were produced between 2018 and 2020 and the resulting fall in timber prices, new investigations into this storage method were initiated. An in-ground storage pilot test was carried out by Saxony State Forestry Service and GALA-MIBRAG-Service GmbH (Elsteraue) under the scientific supervision of Dresden University of Technology, Chair of Forest Utilisation, on (former) open-cast

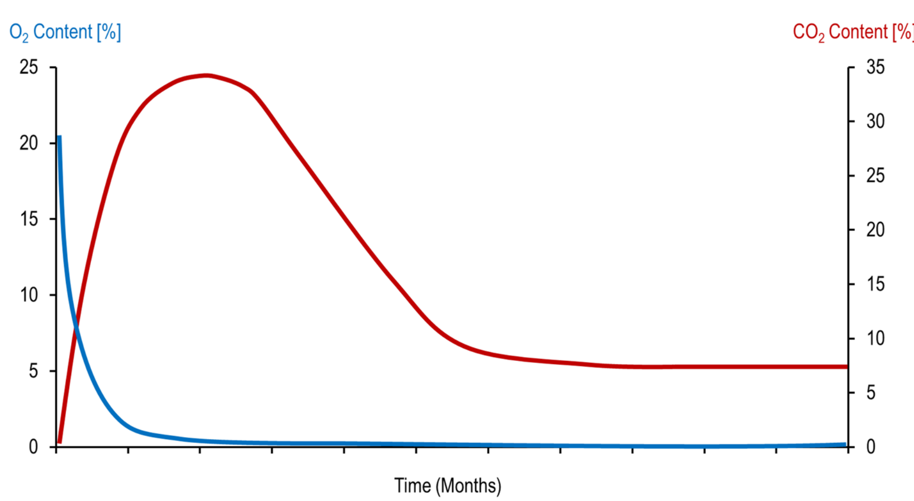

Fig. 3 Schematic illustration of the oxygen (O_2) and carbon dioxide (CO_2) content within the foil pile (Baden-Württemberg method) based on the study of [60]

Fig. 4 Poplar wood stored in foil piles, top left: Superficial growth of fungal mycelium, top right: freshly sawn end grain surface of a poplar log stored for 21 months below: Scanning Electron Microscope images of the poplar log stored in bark over a storage period of nine months with visible bacterial infestation, radial surface. Data basis: [60]

lignite mining areas south of Leipzig. At the beginning of October 2020, around 50 m^3 of roundwood (sections of 5 m length) were stored in two piles. One pile was build up with fresh wood matching RVR-quality grade B/C (Table 2) and one pile with calamity wood lightly infested by bark-breeding beetles. The large quantities of gypsum from flue gas desulphurisation stored in the region should be used for covering. Due to its fine pores, gypsum was assumed to provide an effective seal between the atmosphere in-ground and the outside climate. Fresh wood chips were used as a separating layer (30—50 cm thick) between the logs and the a 1 m thick gypsum layer (Fig. 5).

The O_2 and CO_2 concentration as well as the temperature and humidity in the pile were monitored over a storage duration of 1.5 years.

During storage, a similar atmosphere developed in both piles. The O_2 concentration fluctuated between 0 and 4%. The CO_2 concentration was mostly above 11% (Fig. 6).

The wood moisture content dropped in both piles during storage. The initial average wood moisture content of the fresh logs was 101% and decreased to 86% after a storage duration of 18 months, while the bark beetle infested logs dried from 76 to 64% [4]. This drying process was presumably favoured by the high temperatures in the piles, which were predominantly between 25 °C and 33 °C. The temperature in the piles remained largely unaffected by the outside temperature (Fig. 7). The gypsum probably also absorbed moisture from the wood and was therefore, contrary to the original assumption, not a suitable covering material. In general, the low initial wood moisture content, especially of the beetle infested wood, was unfavourable for successful storage.

Table 2 Characteristics of bark beetle infested Norway spruce wood and quality grading according to [54]

Characteristic		Quality classes			
		A	B	C	D
Insect gallery	< 2 mm	Not permitted	Not permitted	Not permitted	Not permitted
	≥ 2 mm	Not permitted	Not permitted	Not permitted	Not permitted
Decay	Early decay	Not permitted	Not permitted	Permitted in the outer wood layer of the root flare up to 15% of the diameter	Permitted
	Ad-vanced decay	Not permitted	Not permitted	Not permitted	Permitted in the outer layer of the root flare
Discoloration		Not permitted	Slight seasonal surface blue stain permissible	Initial surface discoloration permitted	Permitted
Infestation with bark-breeding beetles		No regulation	Freshly infested, no feeding galleries, bark is still attached to the trunk, and the wood shows no discoloration	Feeding galleries visible, ma-ternal galleries with initial larval feeding, initial surface discolor-ation (blue stain), bark mostly attached, not stem-dry	Blue stain with red streaks, mostly without firm bark, stem-dry, but still suitable for split-ting and nailing

Fig. 5 In-ground storage of Norway spruce logs in a gypsum substrate on a gypsum storage area of MIBRAG in a former mining field south of Leipzig, Germany, top left: Aerial view of the storage site with both piles of 25 m^3 of Norway spruce wood each, top right: pile with slightly infested bark beetle wood, installation of the measuring equipment, bottom: pile covered with gypsum

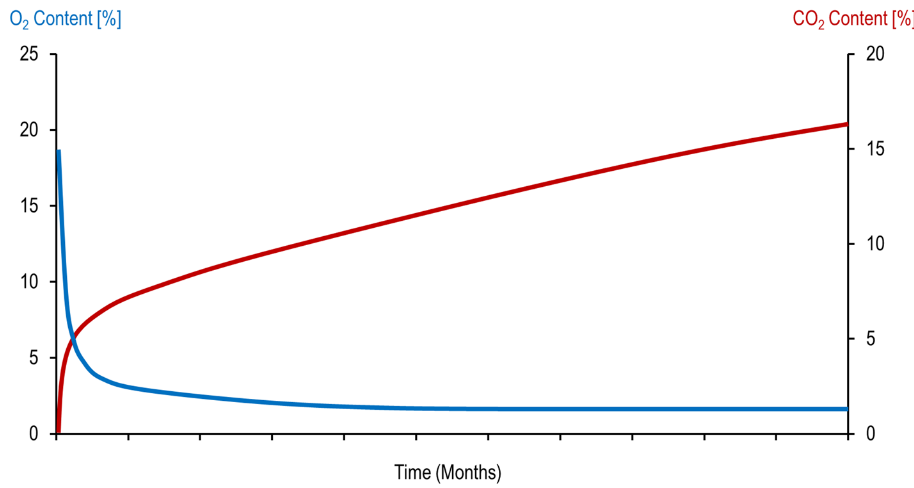

Fig. 6 Schematic illustration of the oxygen (O_2) and carbon dioxide (CO_2) content within the pile in the in-ground storage based on [4]

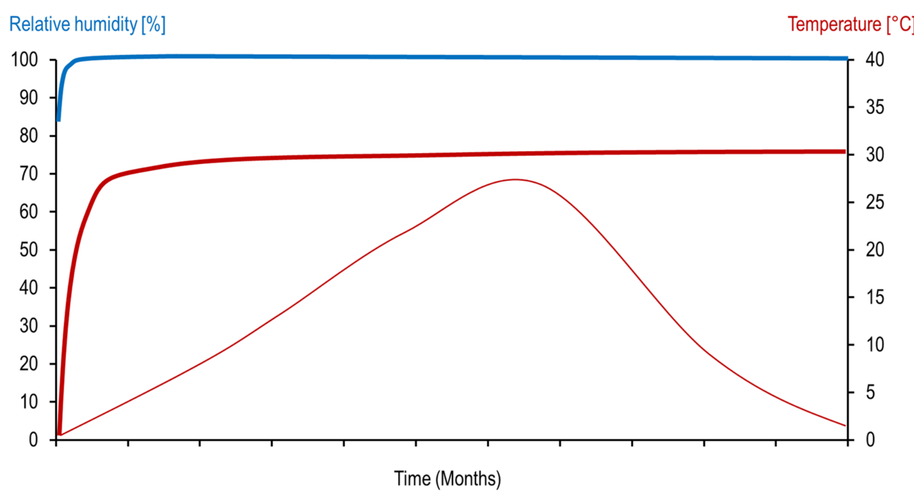

Fig. 7 Schematic illustration of the relative humidity (%) and temperature (°C) within the pile (bold lines) in the in-ground storage and the outside temperature (thin line) based on [4]

The damage led to classification as industrial timber, i.e. RVR-quality grade D (Table 2), which meant that the wood quality could not be maintained by in-ground storage. Additional humidification is required for the storage of bark beetle infested wood, making a layer of woodchippings unnescessary. If woodchippings are used as an intermediate layer, they should be moist and of high quality (Fig. 8).

Due to the rapid price development between 2020 and 2022, around three times the revenue was achieved for the wood compared to the time it was stored [56], despite being categorised as quality level D according to RVR. This shows that another important goal of calamity wood storage, in addition to maintaining timber quality, is to stabilise the log price (and relieve the market).

For future calamities, it remains important to expand the range of quality-preserving storage options and to make the best possible use of local conditions. Even if the wood quality could not be maintained by the in-ground storage carried out here, the results provided important findings for follow-up investigations.

Fig. 8 Removal of in-ground stored Norway spruce logs

2.5 Standing storage (snags)

Out of necessity, Norway spruce logs have recently been stored standing in the forest. In order to cope with the enormous quantities of calamity wood, previously established storage methods such as sprinkling and foil storage were not sufficient. So-called snags, i.e. drying Norway spruce trees after infestation with bark-breeding beetles remained unfelled ("standing") in the forest until capacities for harvest and processing became available again. While sawmills and other wood processing industry have come to terms with this previously little-known raw material, scientific investigation into the influence of upright storage on wood quality have been started.

Within the German research project "NUKAFI" (Utilization of standing-stored damaged spruce timber from calamity areas for the production of wood-based materials and bonded solid-wood products for the construction industry and furniture manufacture) several research questions related to the utilization of Norway spruce snags were addressed.

Based on several stands from the Harz mountains and the Sauerland region, site-factors like water supply or altitude which are potentially influencing the storage and the round wood quality (e.g. rot, discoloration or cracks) of the snags are analysed in relation to the external appearance. Herefore, an initial study showed that although the proportion of crown breakage of standing stored Norway spruce trees increased quite rapidly with increasing standing storage duration, the crown breakage varied widely and this variation could not be attributed exclusively to the watersupply at the sites. These impressions were also confirmed by a more detailed study, in which a wider range of bark beetle infested Norway spruce stands in the Harz mountains were analysed [66]. In an ongoing study, wood moisture content is monitored in snags which remained for different periods in the forest. In addition, the spread of discolouration and wood rot along the trees will be determined and fungal diagnostics will be carried out. To investigate the influence of standing storage on the mechanical properties, specimens will be produced and tested in laboratory and industrial scale. A guideline for forest owners and wood processors with recommendations for dealing with bark beetle infested, standing stored Norway spruce wood is in progress [9].

2.6 Live storage

Live-storage is the storage of windthrown trees in an unchanged position, without separating the trunks from the root ball [11]. Similar to the upright storage of snags, it is

Fig. 9 "Calamity wood dry storage" in the Sauerland region in Germany. Left: Norway spruce sections with a cover from above. Right: Protection from direct contact with the ground by crossing logs

not a storage method in the closer sense, but a type of storage of calamity wood that arose out of necessity [13]. Particularly after the hurricanes Vivian and Wiebke in 1990, numerous trees remained in the forest after windthrow. Studies by Bücking et al. [11] showed that the live-storage of Norway spruce, Scots pine (*Pinus sylvestris* L.), Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco) and oak (*Quercus spec.*) over a period of at least one growing season can be a sensible and economical alternative to conventional storage in heap piles, while maintaining the quality of the wood at the same time. However, the expected quality of the wood after storage depends on the forest location, the extent of the windthrow (extensive or only individual trees), the type of wood and the extent to which the root plate and soil are still connected [22, 23, 42]. Damage caused by blue stain and wood-destroying insects must be expected and the method is only suitable to a limited extent for medium to long-term storage of the wood [31, 42]. It is also important to consider the current forest protection situation, the bark beetle population should always be as low as possible, to prevent excessive propagation from these trees.

2.7 Dry storage

The term "dry storage" is not used exclusively in the context discussed here. On the one hand in contrast to wet storage, the roundwood in dry storage does not undergo any additional humidification. On the other hand, drying does not always take place. Dry storage of fresh wood with bark (without a cover to protect it from rain) aims at maintaining high wood moisture content as long as possible [61]. This exposes the wood to a high risk of degradation and damage, making this approach unsuitable for the long-term storage of roundwood. For coniferous and beech wood, storage for a maximum of one vegetation period is therefore considered practical; beyond this, insect and fungal infestation lead to high quality losses [47, 69].

On the other hand, roundwood can be stored without bark (debarked) and/or under a cover. This is done with the aim of lowering the wood moisture content to such an extent that it falls below cell wall saturation to make it unfavourable for fungal decomposition [45]. Piles with a volume of up to several hundred cubic metres are covered with PVC-coated polyester fabric ("truck cover"), for example. To prevent rotting, it is necessary to avoid direct ground contact of the logs and thus ensure the most successful preservation of fresh wood (Fig. 9) [26].

Dry storage (without bark) is particularly suitable for bark beetle infested wood, as these trees are usually already dead and pre-dried in the stand, which is favoured by a decreasing bark cover with increasing standing time. Ideally, the logs should be pre-dried as evenly as possible. If possible, particularly moist logs should be excluded from dry storage; a requirement that is difficult to realise and control in practice.

Due to the current situation, some forest owners and companies have taken up the conservation method described above in recent years and have set up so-called “calamity wood dry storage” in many places. In contrast to conventional dry storages, the aim was to achieve the lowest possible wood moisture content, ideally at about 30% already at the beginning of storage. Depending on the annual cutting capacity and structure of the sawmills, different requirements were placed on the dry stores and their construction and positioning. In the timber piles of sawmills with annual cutting volumes of several 100,000 m^3 and correspondingly large “calamity wood dry stores”, the piles are packed relatively tightly in order to restrict air circulation. The latter is reducing the drying potential in the store and actual weather conditions play a minor role; logistical considerations such as easy delivery and removal of the wood are more important and are the main focus when selecting the location. Small and medium-sized sawmills often store logs of larger dimensions. This makes the pile structures more inhomogeneous and increase the overall air flow. When selecting a storage site, greater attention is given to factors such as solar radiation, wind exposure and precipitation, etc., which contribute significantly to the development of wood moisture in the pile [26]. In both cases, a storage period of at least one year is aimed for, which is also different from the dry storage facilities commonly used in practice. Those are often set up as temporary storage facilities for a short period of a few months.

3 Conclusions

The occurrence of extensive calamities, such as droughts or bark beetle infestations, not only causes immediate damage but also leads to a loss of timber quality due to the need for medium- to long-term storage. In order to counteract such quality losses and to relieve the timber market, it is essential to establish storage methods that can also be used under unfavourable conditions, e.g. in drought years. This overview highlights that the special features and advantages of suitable storage methods are not generally known and that the methods are not always applied in the best possible way.

Several storage concepts have been developed and tested in recent years, each with distinct benefits and limitations. Wet storage conserves timber for several years but raises concerns regarding sustainability due to decreasing water availability and the risk of soil contamination. Foil storage methods, such as the “Baden-Württemberg method”, provide reliable conservation by fully excluding oxygen, albeit at higher costs compared to the “Swiss method”. Both approaches face challenges when storing logs from beetle-infested trees. In-ground storage, a novel solution, effectively reduces oxygen exposure but requires further research, particularly regarding wood moisture content. Live storage, can maintain wood quality for at least one growing season. Additionally, standing storage and calamity wood dry storage offers practical options for managing large volumes of beetle-affected Norway spruce, despite limited scientific data so far.

Given the unpredictable nature of calamities and their significant impact on the timber market, guidance on the selection and implementation of storage approaches remains vital. In some situations, combining different methods may be beneficial, as it can extend the storage period and thus positively influence market stability. Ongoing research and practical experience are indispensable for the continued improvement and targeted use of these promising storage methods, both for Norway spruce and other tree species that may be affected in the future.

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Author contributions
J.-F.T., C.B., N.S., B.G. and A.M. wrote the manuscript text. J.-F.T prepared the figures. All did the proofreading. N.S. and C.B. provided informations about the investigations regarding the foil storage section. N.S., B.G. and A.M. provided informations about the investigations regarding the in-ground storage section. H.M, C.B. supervision and project administration.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable

Competing interests
The authors declare no competing interests.

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