

Review

What Happens to Wood after a Tree Is Attacked by a Bark Beetle?

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Abstract: Advancing climate change is affecting the health and vitality of forests in many parts of the world. Europe is currently facing spruce bark beetle outbreaks, which are most often caused by wind disturbances, hot summers, or lack of rainfall and are having a massive economic impact on the forestry sector. The aim of this research article was to summarize current scientific knowledge about the structure and physical and mechanical properties of wood from bark beetle-attacked trees. Spruce stands are attacked by a number of beetles, of which *Ips typographus* is the most common and widespread in Central Europe. When attacking a tree, bark beetles introduce ophiostomatoid fungi into the tree, which then have a greater effect on the properties of the wood than the beetles themselves. Fungal hyphae grow through the lumina of wood cells and spread between individual cells through pits. Both white rot and brown rot fungi are associated with enzymatic degradation of lignin or holocellulose, which is subsequently reflected in the change of the physical and mechanical properties of wood. Wood-decay fungi that colonize wood after infestation of a tree with bark beetles can cause significant changes in the structure and properties of the wood, and these changes are predominantly negative, in the form of reducing modulus of rupture, modulus of elasticity, discolouration, or, over time, weight loss. In certain specific examples, a reduction in energy consumption for the production of wood particles from beetle-attacked trees, or an increase in surface free energy due to wood infestation by staining fungi in order to achieve better adhesion of paints or glues, can be evaluated positively.

Keywords: bark beetle outbreak; Norway spruce; wood quality; wood structure; wood physical and mechanical properties



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1. Introduction

Many studies have dealt with the issue of tree infestation by beetles of the genus *Scolytinae* (bark beetle). The attention of scientists has focused mainly on tree attacks [1–3], chemical control and communication [4–8], external factors affecting population size [9,10], and bark beetle development in the larval stage [11]. All these findings have been used not only in the practical application of forest management, but also as potential sources of information for predicting the development of the bark beetle population in individual areas [12].

Bark beetles are important agents of disturbance regimes in temperate forests [3]. *Ips typographus* is the most destructive insect pest of mature Norway spruce (*Picea abies* (L.) Karst) in Europe and can kill millions of trees during bark beetle outbreaks [13,14]. The spruce bark beetle colonizes stressed and dying trees when their populations are low, but then mass-attack large numbers of healthy trees once their populations are high [15]. These spruce bark beetle outbreaks may be triggered by wind disturbances, hot summers, or precipitation deficits [14–16]. Many European countries are currently facing spruce bark beetle outbreaks, which have a massive economic impact on the forestry sector and have serious social and ecological consequences for the landscape [17,18]. Salvage and sanitation

logging spans thousands of hectares and frequently exceeds 50% of the total annual harvest in some central and eastern European countries [15]. At this point, it is important to realize that most of Europe's forests are commercial forests, which also aim to produce quality wood that brings economic profit. This economic profit should be permanently maintained for these forests in the future while increasing the stability and resilience of forest stands in the conditions of climate change.

Differences in the properties of beetle-attacked trees and noninfested trees can be observed and evaluated at several levels. These are differences in the structure of wood (which are observable mainly by various microscopic imaging methods), the physical properties of wood (such as colour or interaction of wood and water), and, of course, the mechanical properties of wood (such as flexural strength and flexural modulus).

At this point, it should be noted that the vast majority of the properties of beetle-attacked trees are affected by the actual bark beetle attack indirectly; this is because the bark beetle in its various stages of development mainly attacks the bast of a living tree, and its larvae mechanically damage the xylem from the tree surface to a depth of a few millimetres. However, these beetles introduce hundreds of fungus and mould species into the tree. Fungi have been found in various parts of the beetle's body, such as the head, prothorax, elytra, proventriculus, and hindgut [19]; these can then have a very significant effect on the properties of wood [20]. The intensity of fungal infestation of wood and the effect of this infestation on the properties of wood is then directly proportional to the length of time for which the fungi act in the wood.

Research teams have investigated the properties of beetle-attacked wood of various tree species. It is obvious that in the region where certain tree species are most affected by bark beetles, the properties of the wood of these tree species are investigated, and in other regions where bark beetles attack other tree species, the properties of those other tree species are investigated. For these reasons, research in Central and Eastern Europe deals mainly with spruce (*Picea abies*, *Picea obovata* Ledeb) [21–23] and in North America mainly pine (*Pinus ponderosa* Douglas ex C. Lawson, *Pinus taeda* L.) [24–27].

Coniferous trees are attacked by a number of bark beetles, the most common and widespread of which are shown in Figure 1. These are *Ips typographus*, *Pityogenes chalcographus*, *Ips amitinus*, and *Ips duplicatus* in Europe [12,15,28] and *Dendroctonus frontalis*, *Dendroctonus rufipennis*, and *Dendroctonus ponderosae* in North America [15,26]. These biotic agents are able to introduce various fungi and moulds into the tree, which then have a greater effect on the properties of the wood than the beetles themselves. Dozens of ophiostomatoid fungus species have been identified that can be introduced into wood along with bark beetles [29].

Economic profit from the sale of wood is the primary source of income in forestry, so it is necessary to determine as accurately as possible the tradable timber volume [30] and, simultaneously, know its quality. The highest quality ranges of wood have several times higher price at the same volume than ranges of lower qualities. For this reason, it is necessary to know what quality of wood we can obtain from these infested trees and what factors influence the quality. The aim of this review article is to summarize current scientific knowledge about the structure, physical properties, and mechanical properties of wood from bark beetle-attacked trees.



Figure 1. Examples of the most common and widespread bark beetle species that attack coniferous trees in Europe and North America.

2. Structure of Wood from Beetle-Attacked Trees

From the point of view of wood structure, only a few millimetres of sapwood around the trunk circumference to a maximum thickness of 3 mm are affected by bark beetle, where spruce bark beetle larvae (*Ips typographus*) form galleries of about 10–12 cm long [31]. However, the total length of the galleries can also be influenced by the density of the bark beetle infestation of the tree, where the length of the galleries decreases with higher tree infestation density [32].

Mechanical damage to the xylem caused by bark beetle larvae on the wood surface of Norway spruce is shown in Figure 2. However, changes in the wood structure are also caused indirectly by the insect infestation, staining, or wood-decay fungi. Fungal hyphae grow deeper from the surface to the centre of the trunk; the rate of wood infestation is given by the length of time from the tree infestation up to the drying of the wood to the moisture level at which the fungi are unable to spread further. This critical humidity is different depending on the type of fungus and tree species, usually in the range of absolute wood moisture 15–30% [33].



Figure 2. Mechanical damage to the xylem of a bark beetle-attacked tree by bark beetle larvae on the wood surface of Norway spruce (*Picea abies*) (own photo).

The depth of Norway spruce wood staining due to symbiotic fungi with *I. typographus* bark beetle was determined in the laboratory. Fungi and yeasts were isolated from beetles using water and alcohol and plated on wood under laboratory conditions. After 21 days, the average depth of staining due to fungi and yeasts isolated from live beetles was 12.5 mm. The most numerous fungi in this case were *Ophiostoma polonicum*, *Ophiostoma bicolor*, *Ophiostoma penicillatum*, and *Graphium* sp. [19]. The staining of Norway spruce wood due to fungi symbiotic with the bark beetle *I. typographus* is shown in Figure 3. The hyphae of these fungi grow through the wood and affect the structure of the wood. These hyphae can be observed by imaging techniques; in Figure 4a,b, fungal hyphae in the wood of Norway spruce infested with *I. typographus* are shown by scanning electron microscopy. Samples were taken from the part of the wood where fungal infestation could be observed visually (colour change), but also from the part where colour changes were not observed. Figure 4a shows that fungal hyphae were also found in wood that visually showed no signs of fungal infestation. Reinprecht [34] stated that fungal hyphae can grow in the longitudinal direction of the trunk up to a distance of several tens of centimetres from the place with visible fungal infestation.

Kržišnik et al. [22] stated that blue or grey wood staining due to colonization by ophiostomatoid fungi does not cause any damage to cell walls, as fungal hyphae grow on the inside of cell walls and only consume nutrients from parenchymal cells without producing wood-degrading enzymes. On the other hand, some wood-degrading enzymes (e.g., pectinase, mannanase) have been detected in blue-stained wood, and growth of fungal hyphae in the middle lamella has also been observed, which can undoubtedly negatively affect the structure of sapwood and thus the mechanical properties of the wood [22,35]. Broda [36] also reported that blue-staining fungi degrade protein content of the parenchyma cells and easily available sugars, but do not degrade structural polymers of wood.

For their study, Howell et al. [27] disintegrated wood from beetle-attacked pine and noninfested pine into very fine particles measuring 75–150 µm. Scanning electron microscope images showed that the particles from the noninfested trees showed more uniform fibre orientation than the particles from beetle-attacked trees, which were characterized by a variable fibre orientation resembling disintegrated, degraded wood. It is clear that the ongoing degradation of the wood mass was caused by wood-decay fungi that colonized the wood after the tree was attacked by the bark beetle [27].



Figure 3. Image of a longitudinal section of bark beetle-attacked Norway spruce wood (on the right), with visible coloration caused by staining fungi (own photo).

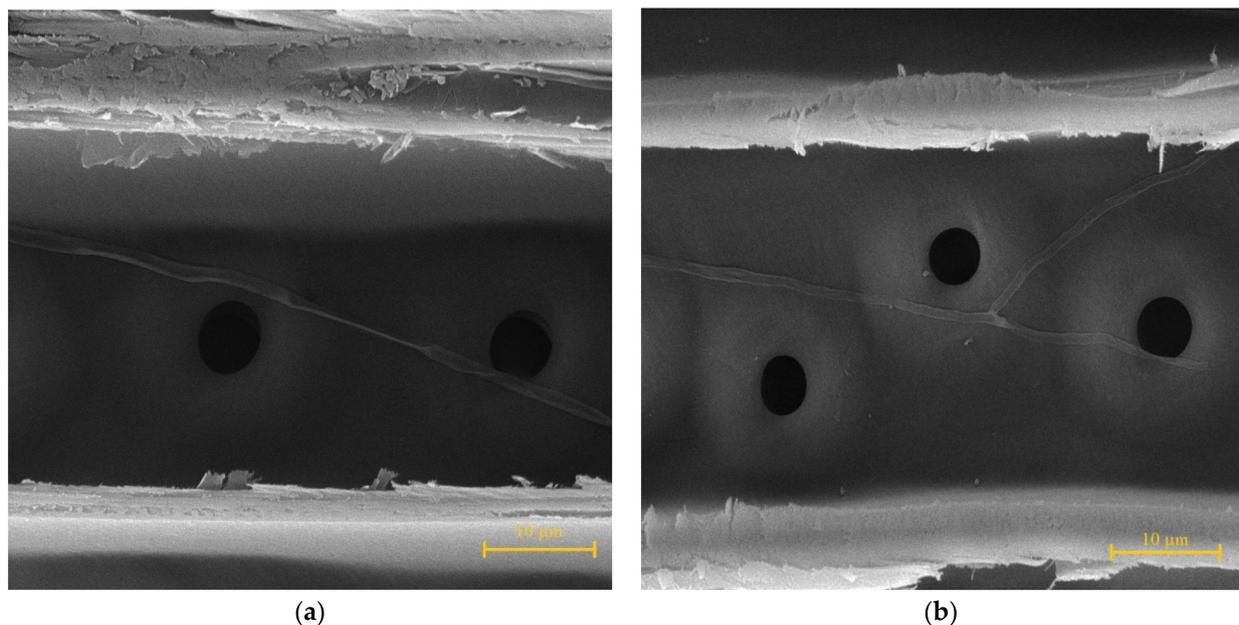


Figure 4. Fungal hyphae in the cell wall lumina of bark beetle-attacked Norway spruce xylem: (a) a sample from the part where fungal infestation was not visually observed; (b) a sample from the part where fungal infestation was visually observed (own photo).

Of the main biomacromolecular substances of which the wood mass is composed (cellulose, hemicelluloses, and lignin), no difference was observed between the wood of the bark beetle-infested and the noninfested tree. However, research on Siberian spruce (*Picea obovata*) infested with European bark beetle *I. typographus* showed that infested spruce wood had a lower tannin content. No effect of attack on resin formation was observed in this study [23]. Hood et al. [24] noted, however, that many coniferous trees increase the amount of resin produced and change their composition after infestation with bark beetle [24,37,38].

3. Physical Properties of Wood from Beetle-Attacked Trees

The research shows that wood from trees infested with bark beetles may show a change in physical and mechanical properties; however, these changes are not caused directly by the insect, but by symbiotic fungi that are introduced into the tree by the bark beetles. The degree of change in physical properties is then given by the length of time for which wood-decay and staining fungi can thrive in wood.

Naturally, blue-stained wood shows a change in colour compared to noninfested wood; in Norway spruce, there was a statistically significant change due to staining fungi in all three coordinates in the colour space, i.e., L^* , a^* , and b^* [22]. However, the interaction of infested wood and water is interesting. Blue-stained wood from beetle-attacked trees showed both statistically significantly higher short- and long-term liquid water uptake than control samples. The difference in water vapour uptake was not statistically significant. These results indicate a higher permeability of blue-stained wood, which is caused by degradation of pits and the formation of new voids [22,39].

The increased permeability of blue-stained wood is also related to durability against wood-decay fungi. Kržišnik et al. [22] have shown that this property is highly dependent on the fungus species. While brown rot fungi *Gloeophyllum trabeum* and *Fibroporia vaillantii* caused a statistically significantly higher mass loss in blue-stained spruce wood, in white rot fungi *Trametes versicolor*, no statistically significant difference was observed between blue-stained wood mass loss and mass loss in control samples. The highest mass loss was caused by *Gloeophyllum trabeum*. At this point, it should be emphasized that, although blue-stained spruce wood has been shown to have lower durability against wood-decay fungi, the durability classification of this wood according to CEN/TS 15083-1 has not been changed because spruce wood itself (as well as beech and poplar) is classified as nondurable wood, i.e., it is in the lowest class [22].

A very important physical property of wood, which is mainly influenced by its chemical composition, is surface free energy. This surface property affects, for example, the surface treatment of wood, but also the gluing of particles in the production of particle boards. Little et al. [26] observed the surface free energy of blue-stained pine sapwood from bark beetle-attacked trees. In this research, a significant effect of the method of drying blue-stained wood on the surface free energy was found. The surface free energy of air-dried blue-stained sapwood of Southern pine was lower than the surface free energy of air-dried control samples. However, when using the technology of drying in batch kiln, the surface free energy of blue-stained wood was higher (and the contact angle between the drop of water and the wood surface was therefore lower) than in the case of noninfested pine wood control samples. The authors therefore suggested that kiln drying can substantially improve adhesion when gluing particles from blue-stained pine sapwood from bark beetle-attacked trees [26]. Similar results (i.e., lower contact angles between the drop of water and the blue-stained spruce wood surface) were obtained in the study of Kržišnik et al. [22]. A comparison of the contact angles achieved in the different studies is shown in Table 1.

In a study on the energy use of bark beetle-infested pines, wood biomass was disintegrated and subsequently torrefied [27]. Torrefaction is a process by which biomass can be modified to obtain more suitable properties for subsequent combustion or co-combustion with fossil fuels [40]. It was shown that wood from beetle-attacked trees showed a higher pyrolysis mass loss than wood from noninfested pines. This is a negative change, as the loss of a large amount of mass during the torrefaction process is not desirable. The higher pyrolysis mass loss compared to control samples is explained by the already-started natural degradation of wood from beetle-attacked pines due to the effect of fungi. On the other hand, wood from beetle-attacked pines also showed higher grindability, which may result in reduced energy consumption for the production of torrefied biomass from beetle-attacked trees [27].

Table 1. Selected physical and mechanical properties of wood from beetle-attacked trees.

Characteristics	Blue-Stained	Control	Specification	References
Modulus of elasticity (GPa)	7.269	10.679	Norway spruce, 3 years decayed	[21]
Modulus of rupture (MPa)	68.93	89.85	Norway spruce, 3 years decayed	[21]
Contact angle with water (°), time of contact 1 s	58.6	72.9	Norway spruce	[22]
Modulus of elasticity (GPa)	9.055	10.79	Norway spruce	[22]
Dynamic contact angle with water (°)	51.1	47	Southern pine, air dried	[26]
Dynamic contact angle with water (°)	40	45.4	Southern pine, kiln dried	[26]

4. Mechanical Properties of Wood from Beetle-Attacked Trees

In the case of the mechanical properties of bark beetle-infested wood, changes in these properties over a longer time horizon (i.e., over a period of several years) may be caused by the action of fungi. In their study, Jelonek et al. [21] dealt with changes in the mechanical properties of bark beetle-infested Norway spruce wood after the beetles had left the stump for several years. Research has shown a declining trend in average values of modulus of rupture (MOR), as well as modulus of elasticity (MOE). A statistically significant decrease was demonstrated only three years after tree infestation, where after three years the MOR decreased from 89.85 MPa to 68.93 MPa and the MOE decreased from 10.679 GPa to 7.269 GPa. Based on these results, the authors stated that stands that have been infested with bark beetles and fungi for three or more years are potentially dangerous for tourists in forests and further suggested that the wood of these trees can be further used in industry for up to two years after bark beetle infestation [21]. Norway spruce wood still meets the standard required strength properties for timber after the first or second year after infestation by bark beetle and can be used for construction purposes. This wood contains fungal spores and hyphae [19], which can activate and begin to grow at any time after rising humidity throughout life cycle of a wooden structure. However, wood can be contaminated with fungal spores not only from beetle bodies, but also from air, where spores are also commonly present [41,42]. Therefore, construction protection of wooden elements is recommended in timber structures [43]. A comparison of selected mechanical properties of wood from beetle-attacked trees is shown in Table 1.

The influence of ophiostomatoid fungi on the MOE of Norway spruce was also researched by Kržišnik et al. [22]. However, the time factor over which the wood is infested was not considered in this research. Control samples and blue-stained samples were compared, with sample density and annual ring thickness being comparable for both sets of samples. It is well known that the density of wood fundamentally affects its mechanical properties [44]. If white rot and brown rot fungi cause a wood mass loss, as the wood density decreases, so do its mechanical properties [45]. This effect was shown in research [21], where the mechanical properties gradually decreased with increasing duration of degradation processes due to fungi. However, Kržišnik et al. [22] in their research compared only the effect of blue-stained wood on its properties; the differences in the density of control and blue-stained samples were not statistically significant. The results showed a statistically significant decrease due to fungal infestation in the MOE of spruce wood from 10.79 GPa to 9.055 GPa. A statistically significant effect of blue staining on compression strength was not observed. The authors were not sure why blue-stained wood showed statistically significantly lower MOE when the density was comparable to control samples. They noted that this difference could also be due to the natural variation of wood [22,46].

The decrease in mechanical properties of wood due to the action of fungi is correlated with the weight loss of wood due to the action of wood-decay fungi. It has been shown that brown rot fungi (which cause degradation of cellulose and hemicelluloses) [36] have a higher negative effect on wood mechanical properties than white rot fungi (which cause degradation of lignin and hemicelluloses, but also cellulose) [36] at the same weight loss of wood. When wood is attacked by brown rot fungi and reaches a weight loss of 2%, the decrease in MOR is on average 32%; with a weight loss of 10%, the decrease in MOR already reaches 55–70%. Conversely, when wood rot is attacked by white rot fungi and

reaches a weight loss of 2%, the average decrease in MOR is 14%, and at 10% weight loss, the decrease in MOR is 24% [47,48].

Based on the performed review, it can be said that the properties of wood as a material are not directly negatively affected by bark beetle attack and can be used for further material use. However, because of the development of wood-decaying and wood-staining fungi, the time for which wood from bark beetle-infested trees can be used is automatically limited in time. Jelonek et al. [21] suggested that spruce wood from stands in Białowieża Forest can be industrially used within two years of bark beetle infestation. However, the degree of fungal infestation of wood depends on wood moisture, which is strongly affected by local climatic conditions. For most wood-decaying fungi, the optimal wood moisture is 30–70% [34,49]. For this purpose, it is recommended to perform tests of wood properties. In the case of the use of wood for non-load-bearing purposes, a visual control is sufficient; in the case of the use of wood for load-bearing purposes, tests of mechanical properties are necessary. In the industrial production of lumber, the use of nondestructive methods for testing the mechanical properties of wood can be recommended. Both MOE and MOR can be controlled using these techniques based on acoustic [50,51] or vibration methods [52,53]. In the case of the need to diagnose the presence of wood-decaying fungi or the degree of infestation of wood by fungi, the imaging and analytical methods of structural analysis can be advantageously used. In the past, Fourier transform infrared (FT-IR) [54–56], Raman spectroscopy [57,58], scanning electron microscopy [55,59], and X-ray diffraction [54,60] have been successfully used to monitor wood decay.

5. Future Challenges

The presented review article summarizes findings from various studies dealing with the effect of bark beetle outbreaks on the quality of wood in infested trees, specifically the structure, physical properties, and mechanical properties of wood. Available information was synthesized, and since the wood of trees infested with bark beetles is also subject to subsequent fungal infestation, the influence of wood-destroying and wood-staining fungi on the properties of wood was also considered. However, research published to date does not answer all the questions related to the wood properties of bark beetle-infested trees. Therefore, this chapter summarizes questions and research topics that would be appropriate to address in the future.

The structure, physical properties, and mechanical properties of wood from bark beetle-infested trees are fundamentally affected by the type of fungus that infects the wood, the moisture content of the wood, and the time period during which the fungi degrade the wood. Isolated effects partly describing this phenomenon occurring in a forest habitat have already been investigated; namely, the influence of the fungus species on the weight loss of wood and reduction of its mechanical properties, the influence of the time period of degradation on the weight and strength loss of wood, and the influence of weather on the drying speed of wood have already been investigated [21,22,26,27,34,49]. Although these isolated effects have been quantified, they do not provide enough information for practical use during bark beetle outbreaks. Foresters are requesting information on how long the properties of wood from bark beetle-infested trees are not negatively affected. It is obvious that this length of time depends on the type of tree species, specific site factors, and season. For this purpose, it is necessary to determine the rate of degradation of a particular wood species by fungi in individual forest height steps in specific seasons.

Other questions are whether the process of wood depreciation proceeds faster on standing trees or on trees lying after felling and whether wood depreciation proceeds faster in the sun or in the shade. This depends on whether the logs are debarked and interspersed and on the weather, because decaying fungi have their optimal wood moistures and temperatures wherein they thrive. Another factor is the position of the fungi in the log, because the moisture content of the wood also depends on the vertical position in the log [34,49]. This information has practical implications for how and when to harvest timber and therefore has to be addressed in further research.

It was shown that bark beetle infestation is not a real threat to wood quality, but the subsequent accompanying phenomenon of fungal infestation of wood reduces the quality of the wood very significantly and can even completely devalue it. Few studies have suggested which applications wood from bark beetle and fungal-infested trees can be used in [21,22,26,27,61]. However, the use of wood from bark beetle-infested trees is certainly wider, and it is necessary to determine how the properties of the final products from bark beetle- and fungal-infested trees are affected.

6. Conclusions

As most of the currently tradable softwood from Europe comes from bark beetle-incident logging, it is essential to know the quality of this damaged timber because of the requirements for its price at the time of sale. Damage to wood by bark beetles does not automatically mean a lower financial value of wood because the quality of the wood depends on various factors. These factors, influencing the structure, physical properties, and mechanical properties of wood from bark beetle-attacked trees, have been described in the current scientific literature, and a synthesis of them is presented in this article.

The wood structure and properties are only slightly affected by the bark beetle itself; only the surface of the sapwood around the wood surface is damaged. More significant changes in the structure and properties of wood after bark beetle infestation are caused indirectly by staining and wood-decay fungi. The degree of wood infestation by fungi and the effect of this infestation on the properties of wood is then greater the longer the fungi act in the wood. A statistically significant decrease in the mechanical properties of Norway spruce infested by bark beetle was not observed until three years after the introduction of wood-decay and staining fungi into the tree. Until the mechanical properties of the wood are reduced, spruce wood infested by bark beetle can be used for construction purposes. Moreover, it can be said that for certain technological applications (based on wood gluing), infestation of wood with staining fungi may not be a disadvantage, or may even be an advantage. For wood infested with staining fungi, an increase in surface free energy and a decrease in the contact angle between water and the wood surface have been observed during industrial drying, which can have a significant positive impact in the production of wood-based composite materials such as particle board, plywood, or OSB (Oriented Strand Boards).

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