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Natural, Accelerated, and Simulated Weathering of Wood: A Review

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This review considers three aspects of the weathering of wood – natural weathering, accelerated weathering, and simulated weathering. Natural weathering begins when unprotected wood, such as an unpainted board, is exposed to cycles of solar radiation and rain. Unpainted barns and fenceposts take on a gray coloration and their surfaces may become rough, loosened, or checked with the passage of time. The underlying causes of such changes involve ultraviolet light, the effects of cyclic wetting and drying, and the action of certain fungi. Accelerated weathering tests have been used not only to evaluate the effectiveness of varnishes and paints, but also to aid in the understanding of factors affecting natural weathering. Simulated weathering usually has the goal of quickly and conveniently changing the appearance of fresh wood to give the impression of weathering. This might increase its appeal for various decorative purposes. Information about simulated weathering, though largely absent from the scientific literature, is very much alive in social media. This article considers the science behind all three types of weathering in the light of published accounts.

Keywords: Ultraviolet light; Solar radiation; Gray coloration; Roughness; Rainfall; Bluestain fungus; Checking

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INTRODUCTION

Weathering of wood, in the context of this article, will be defined as a change in appearance and surface properties of unprotected wood when exposed to outdoor weather conditions. The term also can refer to laboratory conditions intended to predict effects of natural weathering in a shorter time period. It might also refer to treatments intended to impart a weathered appearance to wood. The present review is concerned especially with what happens at the surface of exposed wood, rather than such effects as bulk rotting, fatigue, or any chemical changes that might affect the interior properties of a weathered board. Though one can expect that weathering also will affect wood that has been protected by varnish, paint, or other coatings, such situations are not the focus of this article. Some questions to be considered in this article are as follows:

- What are typical changes that occur when wood is exposed to weather conditions that include sunlight and rain?
- What are the principal causes of changes in such attributes as color, roughness, and the appearance of cracks in wood during natural weathering?
- To what extent can accelerated weathering tests predict the effects of natural weathering?
- In what ways can results of accelerated weathering tests reveal the probable mechanisms responsible for natural weathering?
- What are some cost-effective, generally environmentally benign treatments that might be used to mass-produce wood that meets with the approval of customers who are interested in weathered wood for such purposes as decoration, furniture, or design?

Natural weathering is a process that affects not only cut boards, but also dead standing trees and driftwood (Williams 2005). The appearance of old barns, cedar-shake roofs, and fenceposts can impart a feeling of nostalgia. Such wood, when recovered, often can be sold at a premium price in modern applications on account of its appearance. When one considers the huge numbers of wooden structures around the world that either never were protected by paint, or from which protective layers have peeled away, it is understandable that many researchers would be motivated to find out how and why various changes happen to the surface of the exposed wood. The natural processes are also of interest to companies providing products such as paint and varnishes, the purpose of which is, in part, to protect wood from natural weathering (Panek and Reinprecht 2014, 2016; Turkoglu *et al.* 2015a,b; Kart *et al.* 2018). Important earlier reviews of the topic of natural weathering include those of Feist (1982, 1989), Feist and Hon (1984), Kranitz *et al.* (2016), and Cogulet *et al.* (2018), among others.

The motivation to employ accelerated weathering protocols is a matter of practicality; one desires information about the resistance of various wood materials to weathering – either in their untreated state or when somehow protected – and in many cases one cannot afford to wait many months or years to find the answers. In addition, accelerated weathering conditions make it possible to specify such conditions as UV radiation attributes, moisture levels, and temperatures. Though accelerated tests can give answers more quickly, the results might not be trusted. Questions may be raised regarding whether the accelerating weathering conditions allow a fair prediction of changes that would have occurred as a result of natural weathering. Fortunately, as will be shown, a great many studies have been carried out in parallel, allowing direct comparisons of matched sets of wood specimens exposed either to outdoor weathering or laboratory conditions. The following are some notable review articles focusing on accelerated weathering methods and their use (Back and Sandström 1982; Feist and Rowell 1982).

Various methods can be used to modify wood in an attempt to give an impression of weathering, often with the goal of increasing its sales price. Genuine weathered wood, say from old barns, is often limited in supply, and a high amount of labor may be required to deconstruct the old structure to recover the wood. Thus, a key goal of those who wish to simulate such effects is to decrease the cost of delivering product to customers who desire a product that has a weathered appearance. The effects of weathering on aesthetic perceptions have been studied by systematic interviews (Zanetti *et al.* 2003).

Unlike the topics of natural weathering and accelerated aging, the topic of simulating aging, *i.e.*, modifying wood with the intention of making it appear to be weathered, has been addressed sparsely in the scientific literature. Instead, there has been a voluminous output of YouTube videos and social media postings related to the topic. Part of the objective of this review article is to discuss what can be learned from the social media information and the extent to which the observations have a correspondence with the scientific literature.

Various aspects related to wood weathering have been covered in earlier review articles and monographs. The words "wood aging" often have been used in studies focusing on the effects of time, under dry conditions; such effects have been reviewed by Cavalli *et al.* (2016) and Kranitz *et al.* (2016). Sell (1975) and Cogulet *et al.* (2018) discuss wood weathering in the context of requirements for surface treatments, including paints and varnishes, when the goal is to prevent weathering. A book by Zabel and Morrell (1992) covers the broad topic of wood decay, in addition to discussing bluestain issues that occur during natural weathering or wood. Researchers studying the natural weathering of wood have benefited from the excellent monographs of Feist (1982, 1984) and also from a chapter by Feist and Hon (1984). The present review article covers natural, accelerated, and simulated weathering of wood, with attention to governing mechanisms and recent trends.

NATURAL WEATHERING

This section, dealing with natural weathering of wood, will consider three main aspects. First, typical observations will be described, in terms of changes in color, roughness, crack development, and wood properties. Second, the influence of site conditions, such as the direction relative to the sun, will be considered. Third, mechanisms that have potential to explain effects related to natural weathering will be described.

Typical Observations

Color

The most widely noted effect of long-term exposure of unprotected wood to outdoor weather, including periods of sunlight and rain, is a change in wood's surface color. Commonly reported trends are summarized in Table 1, along with selected references. To summarize, the initial changes in color toward yellower or browner hues have been described as relatively rapid. Such changes are often perceptible relative to unexposed wood within the first days of outdoor exposure. The change in color during this initial period has been described as linear with time (Dunningham *et al.* 1992). In the longer term, however, the wood becomes less yellow and less red, tending toward a gray color. Whether or not the final stage can be regarded as "darkened" or "bleached" differs from case to case, since wood species have large differences in their initial color before exposure. Wood's initial color, prior to weathering, also will be influenced by such factors as drying conditions, thermal treatments, and periods of storage.

Yildiz *et al.* (2011) reported relatively large effects of natural weathering on the color of alder wood that previously had been heat-treated at either 150, 180, or 200 °C. The heat-treatment caused progressive darkening of the wood, while the wood became somewhat less red and less yellow. Subsequent natural weathering remarkably lightened the wood and further decreased the red and yellow coloration. Ayadi *et al.* (2003), Huang *et al.* (2012a), and Garcia *et al.* (2014) reported that the color-stability of several types of heat-treated wood during artificial weathering was greater compared to untreated wood. By contrast, Cui and Matsumura (2019) observed decreasing changes in color during natural weathering of *Cunninghamia lanceolata* (Lamb.) Hook. in the following order: heat-treated at 220 °C > untreated > heat-treated at 190 °C.

Table 1. Reported Changes in Wood's Color Due to Natural Weathering

Reported Change	**Selected Citations**
Initial yellowing or deeper brown coloration	Schramm 1906; Browne & Simonson 1957; Feist 1982; Feist & Hon 1984; Tolvaj & Faix 1995; Wang *et al.* 1998; Uzunovic *et al.* 2008; Ruther & Jelle 2013; Yildiz *et al.* 2013; Mattos *et al.* 2014; Schnabel & Huber 2014; Teles & da Costa 2014; Xing *et al.* 2015; Liu *et al.* 2016; Papp *et al.* 2016; Yalcin *et al.* 2017; Petrillo *et al.* 2019
Long-term establishment of a stable, gray color	Browne & Simonson 1957; Forest Products Laboratory 1966; Arndt & Willeitner 1969; Feist 1982; Feist & Hon 1984; Wang *et al.* 1998; Williams 2005; Uzunovic *et al.* 2008; Huang *et al.* 2012a,b; Ruther & Jelle 2013; Yildiz *et al.* 2013; Budakci & Karamanoglu 2014; de Castro *et al.* 2014; Mattos *et al.* 2014; Schnabel & Huber 2014; Teles & da Costa 2014; Gonzalez de Cademartori *et al.* 2015; Liu *et al.* 2017
Thickness of gray layer limited to about 2 to 5 mm	Forest Products Laboratory 1966; Sell 1968; Feist 1982; Han *et al.* 2019
Trend toward a stable color relatively independent of the initial color of the wood	de Castro *et al.* 2014; Liu *et al.* 2019
Brown layer beneath the outer gray layer at the wood surface	Browne & Simonson 1957
Blue tint and gradual darkening after long exposure	Humar *et al.* 2008; Uzunovic *et al.* 2008; Adamopoulos *et al.* (2011)

Some of the reported changes cited in Table 1 have been reported by relatively few investigators. Further research may be needed in those areas to back up the findings and to establish whether they have general validity. For example, it would be interesting to better define the conditions (type of weathering, time of exposure, wood type, *etc.*) governing the existence and thickness of a brown layer below an outer gray layer at the surface of weathered wood (Browne and Simonson 1957). Also, using modern analysis tools, there is an opportunity to characterize the chromophoric substances, *e.g.* determining whether they are byproducts of the decomposition of lignin.

To summarize the main effects of natural weathering on color, Table 2 reports the average values for color based on 28 sets of reported data. The color is specified based on the CIELab system (Broadbent 2004). A full listing of the source data is provided in Table A (see Appendix). According to the CIELab system, the quantity L^* corresponds to the lightness of the material, with 100 representing an ideal white and 0 representing a pure black. The quantity a^* indicates the degree of redness (if positive in value) or greenish appearance (if negative). The quantity b^* indicates the degree of yellowness (if positive) or blueness (if negative). One unit of change in any of the parameters can be taken as an approximation of a typical perceptible difference for objects having uniform coloration under ideal lighting.

Table 2. Average Effects of Natural Weathering on Color Attributes of Wood after Brief or Long-term Exposure

Time of testing	*L**	*a**	*b**
Initial	69.1 (10.5)	8.4 (4.3)	20.8 (3.4)
Short time §	62.0 (11.7)	7.8 (3.5)	21.1 (8.1)
Long time §§	51.2 (9.8)	3.1 (3.6)	9.1 (7.8)

Notes: Mean values and (standard deviations) shown; § Short time was selected as either the earliest reported non-zero elapsed time of a given study, or if available, a time corresponding to a maximum increase in *a** value. §§ Long time always represented the longest duration of exposure for each study. Data from the following studies were considered: Delucis *et al.* 2016; Gonzalez-C. *et al.* 2015; Kržišnik *et al.* 2018; Liu *et al.* 2017; Machova *et al.* 2019; Mohebby and Saei 2015; Oberhofnerová *et al.* 2017; Ozgenc and Yildiz 2016; Panek and Reinprecht 2016a,b; Reinprecht and Panek 2015; and Turkoglu 2015b. There were 28 sets of values averaged for initial and long-term data. There were 27 sets of values averaged for short-term data.

An example of the appearance of weathered wood, including its color, is provided in Fig. 1. In this case, the image on the right corresponds to a tangential surface of the red oak (*Quercus rubra*) wood board that had been facing the weather. The left-hand image depicts the backside, not facing the weather, of the same board.

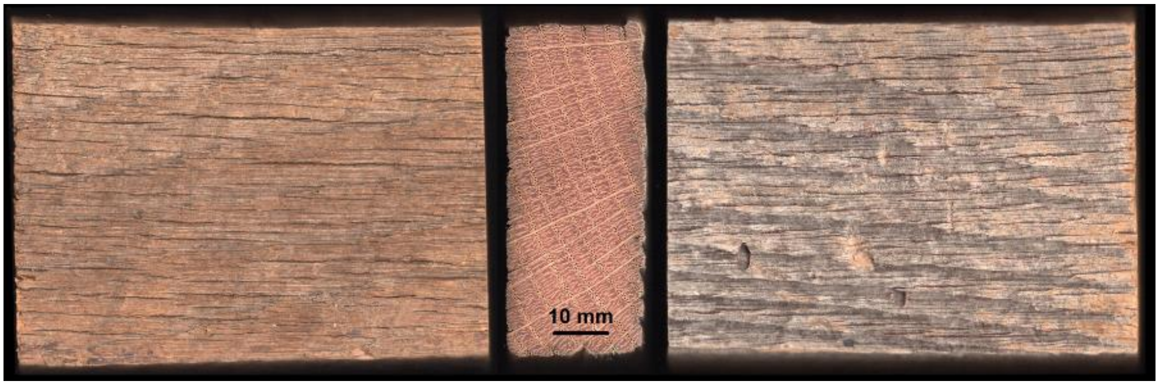


Fig. 1. Example of weathered red oak (*Quercus rubra*) wood. The right side of the board was exposed to the weather, whereas the left side was covered.

The central image shows the end grain, as well as revealing some aspects of roughness on the other faces, especially the weathered surface (see later discussion). Note the grayer and less red appearance of the weathered (right-hand) image in comparison to the left-hand image. The non-uniformity of coloration is also worth noting in this example.

To summarize the findings, the general trend was that wood specimens eventually became darker (lower $L*$ value), less red ($a*$ value lower and nearer to zero), and less yellow ($b*$ value lower and nearer to zero). "Graying" is a general term to sum up all of these trends, when considering the effects of long-term exposure. However, it is important to note that the short-term effects often did not correspond to the long-term trends. In many specific cases, relatively short-term exposure to natural weathering increased the values of $a*$ especially, and sometimes $b*$ as well. In other cases, due to differences either in species or test conditions, the short-term effects were more in line with the long-term effects.

Roughness

A second very commonly reported observation of the effects of weathering is that the wood surface becomes rougher, often on a fine scale. Such observations are summarized in Table 3. Among the publications cited in this review, the term "rough" generally has been used when describing features in a size range from about 0.5 to several mm. Such features include corrugated annual rings and protruding, loose fibers.

Regarding the reports of "corrugated" morphology, coinciding with annual rings, it has been reported that the latewood, which is denser, tends to be more resistant to weathering than the earlywood, which tends to recede more quickly in the course of weathering (Feist 1982; Feist and Rowell 1982; Williams *et al.* 2001b,c; Williams 2005; Hazneza and Evans 2016; Petrillo *et al.* 2019). A logical interpretation might be that the denser parts of the wood are simply stronger and more resistant. As a possible alternative explanation, Miniutti (1964) suggested that at least part of the effect might be attributed to crushing of springwood during planing of the wood; upon rewetting of the wood, the crushed structures would be expected to rebound, giving rise to a corrugated surface. Such a mechanism, however, does not explain why the latewood would mainly comprise the raised ridges, as shown in cross-sectional micrographs (Williams 2005). The development of voids at the microscale has been reported only once (Evans *et al.* 2008) to the best of the authors' knowledge. Accordingly, this could be a useful area of focus for future research.

Table 3. Reported Increased Roughness of Wood Due to Natural Weathering

Reported Change	**Selected Citations**
Increased roughness in general	Forest Products Laboratory 1966; Kudela & Ihracky 2014; Tomak *et al.* 2014; Kerber *et al.* 2016; Oberhofnerová *et al.* 2017; Saad *et al.* 2017
Corrugations coinciding with the annual rings	Miniutti 1964; Feist 1982; Feist & Rowell 1982; Williams *et al.* 2001b,c; Williams 2005; Hazneza and Evans 2016; Petrillo *et al.* 2019
Loose, matted fibers on the surface	Browne & Simonson 1957; Feist 1982; Nilsson and Daniel 1989; Xiao 2012; Hazneza and Evans 2016
Wrinkled fibers	Dunningham *et al.* 1992
Development of voids at the microscale	Evans *et al.* 2008
Loss of wood thickness after long exposure	Feist & Rowell 1982; Williams 2005

An example of a weathered piece of white oak (*Quercus alba*) wood that shows substantial roughness is provided in Fig. 2. In this case, the right-hand image corresponds to the weathered surface. Note the profile of the right side of the central section of this composite figure. It is apparent here that material had been removed in an uneven manner from the wood surface. The erosion left an uneven surface with some cracks extending inward. The topic of cracks is considered next.

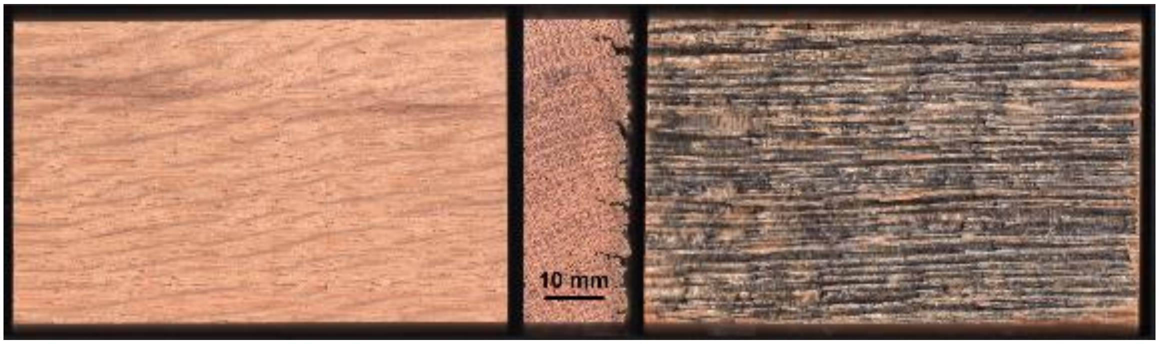


Fig. 2. Example of weathered white oak *(Quercus alba)* wood. The left side of the board was planed; the right side shows a deep relief due to erosion by weathering.

Cracking

In reporting cracks and related features in weathered wood, it has been noted that very small cracks may appear initially, and these can be followed by larger cracks at longer times of weathering. Reported observations of this type are summarized in Table 4. Microscopic examination of weathered wood by Miniutti (1964) showed that some cracks were within individual beech wood fibers, where they generally followed the microfibril angles of the predominant S2 sublayers. Other micro-scale cracks coincided with the middle lamella regions between some of the adjacent fibers. Xiao *et al.* (2012) likewise observed cracks within individual softwood tracheids.

Table 4. Reported Cracks and Checks in Wood Due to Natural Weathering

Reported Change	Selected Citations
Cracks in general	Feist 1982; Feist & Rowell 1982; Oberhofnerová *et al.* 2017
Micro-cracks	Miniutti 1964; Kishino & Nakano 2004a,b; Huang *et al.* 2012b; Gonzalez de Cademartori *et al.* 2015; Xing *et al.* 2015; Reinprecht *et al.* 2018a
Macro-cracks	Feist 1982; Sandberg 1999; Sandberg & Söderström 2006; Xiao *et al.* 2012; Reinprecht *et al.* 2018a
Checking	Forest Products Laboratory 1966; Feist 1982; Feist & Rowell 1982; Evans *et al.* 2008; Panek *et al.* 2017

At the macro-scale, Sandberg (1999) observed that the frequency and depths of cracks tend to be much greater on exposed tangential surfaces of wood than on the corresponding radial surfaces. The ratio between tangential and radial surface crack lengths was observed to be 6 in the case of spruce and 13 in the case of pine.

The word "checking" appears to have a range of meanings in the published literature, including large cracks extending outwards from the heartwood of a tree and apparently brought about by extensive shrinkage of the sapwood, which surrounds the heartwood. Also, it can refer to the development of large cracks during drying of certain lumber types, such as acacia (Tenorio *et al.* 2012). Checking is also a term used for cracks that develop in the end of logs when they are cut and allowed to dry before being delivered to the sawmill (Linares-Hernandez and Wengert 1997). When the word has been used to describe surface effects, it is often used to describe much smaller features. For instance, Feist (1982) stated that "Checking in the wood may eventually grow into large cracks." Williams (2005) describes the development of checks starting at bordered pits, which are micrometer-scale features at fiber surfaces. Miniutti (1964), Dunningham *et al.* (1992) and Evans *et al.* (1994) referred to "micro-checks". Jebrane *et al.* (2017) appear to use the word "check" as a synonym for "crack", as in the phrase "check propagation". Osawa *et al.* (2019) observed that some checks were 20 mm in depth from the wood surface. In the present article the word checking will be used when referring to cracks in weathered wood that extend inward from the exposed surface. They are often arranged in a series of parallel cracks. As discussed in a later section, they appear to be related to cycles of wetting and drying of the wood.

Figure 3 provides an example showing the development of micro-cracks in a specimen of red oak (*Quercus rubra*) wood. Detail 3.1 shows the crack formation starting on a medullary ray but deviating from it and breaking its way through the vessels into the late wood xylem. Detail 3.2 shows a typical crack formation for oak along the medullary ray in radial direction. The crack formation along the rays can partially explain the higher frequency and depth of cracks on tangential surfaces, compared to radial surfaces, as described by Sandberg (1999).

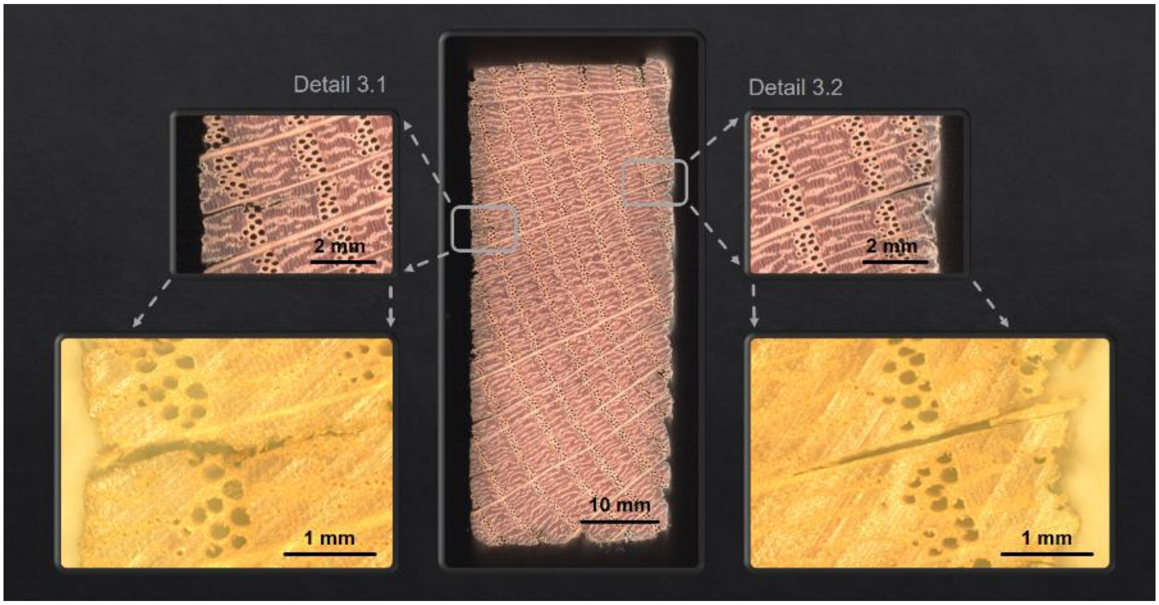


Fig. 3. Example of weathered red oak (*Quercus rubra*) wood showing the development of microcracks. The details in the cross-section correspond to Fig. 1.

Figure 4 shows a case in which an individual crack on the weathered (right) side of white oak (*Quercus alba*) wood extended into the material and then stopped at a medullary ray feature (Detail 4.1). The crack continues in radial direction along the medullary ray. As discussed before, it can be seen in the image that the earlywood part, with its higher porosity and lower cell wall thickness, is more susceptible to degradation, such as roughening and loss of surface material, due to weathering.

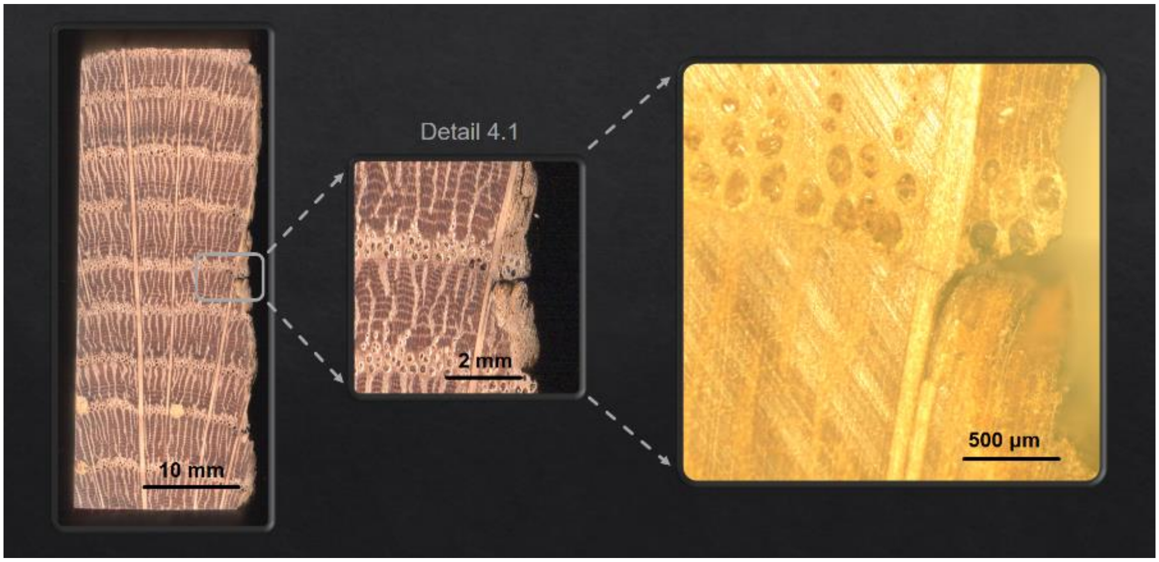


Fig. 4. Example of weathered white oak (*Quercus rubra*) on radial surface

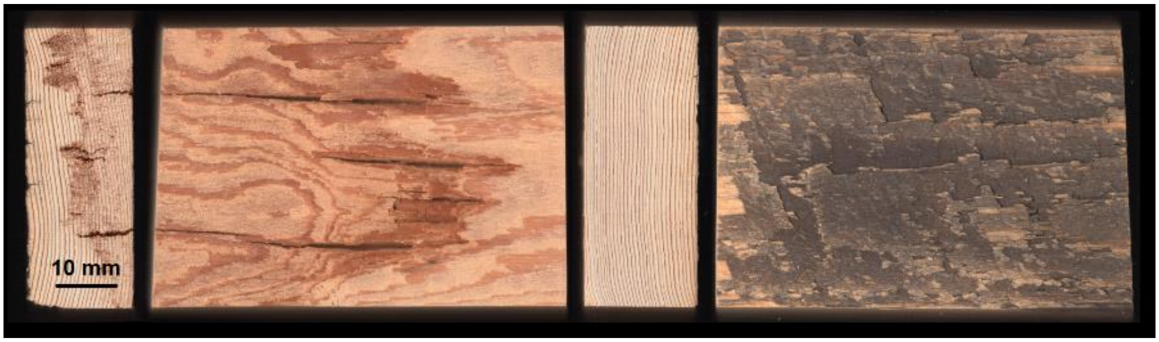


Fig. 5. Example of weathered eastern hemlock (*Tsuga canadensis*) on tangential surface. Left side degraded by fungi due to long-term moisture accumulation; right side exposed to weathering.

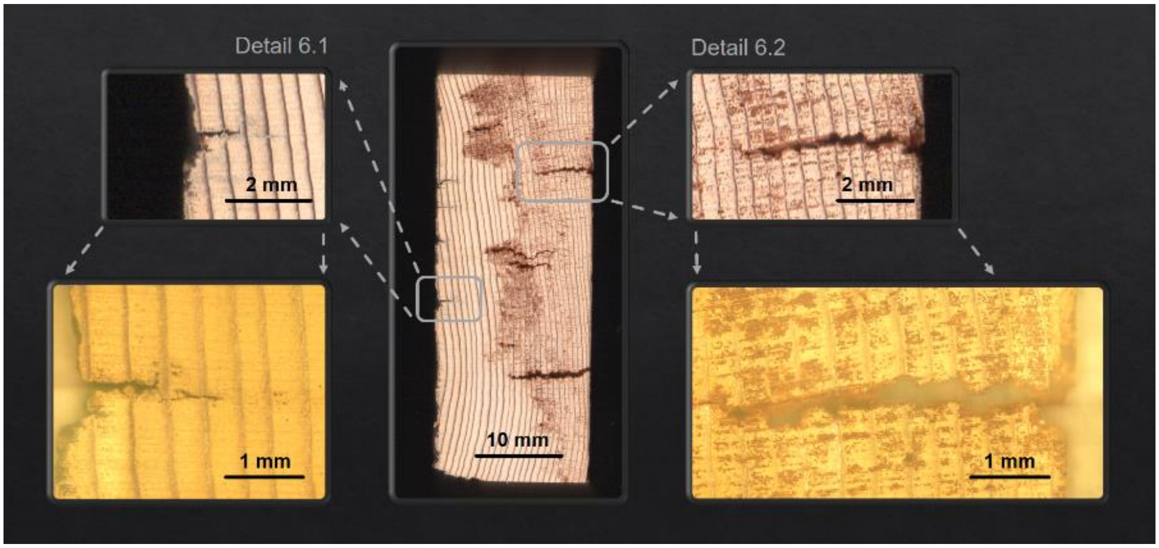


Fig. 6. Example of weathered eastern hemlock (*Tsuga canadensis*) on tangential surface. The cross-section and details are corresponding to Fig. 5 above.

Figures 5 and 6 show images from a specimen of eastern hemlock (*Tsuga canadensis*) wood with contrasting effects on two sides. The left side shows a weathered tangential surface. The surface layers of the wood specimen are peeling off due to erosion. Crack formation in the radial direction accompanies the delamination of the surface layers, which is visible in detail 6.1. The right side of the figure shows the wood substance degraded under long-term moisture influence. Wood-deteriorating fungi colonize the moist wood substance and degrading the structure. Massive crack formation in radial direction takes place consequentially, as visible in detail 6.2.

Wood properties

In addition to visually obvious changes, such as color, roughness, and cracks, it is reasonable to expect that weathering will change some non-visible properties, such as wettability, strength, crystallinity, and chemical compositions. Reports of such changes are summarized in Table 5.

Table 5. Other Reported Changes in Wood Properties Due to Natural Weathering

Reported Change	**Selected Citations**
Strength properties (no consistent trend)	Back & Sandström 1982; Deppe and Schmidt 1991; Derbyshire *et al.* 1996; Soares del Menezzi *et al.* 2008; Kojima & Suzuki 2011a,b; Kim & Matsumura 2013; Cavalli *et al.* 2016; Jankowska & Kozakiewicz 2016; Oberhofnerová *et al.* 2016; Almeida *et al.* 2019a
Wettability (generally more wettable)	Kishino and Nakano 2004a,b; Williams 2005; Huang *et al.* 2012b; Gonzalez de Cademartori *et al.* 2015
Chemical changes	
Lignin (decreases in lignin near to the surface)	Forest Products Laboratory 1966; Arndt & Willeitner 1969; Feist 1982; Hon & Feist 1986; Anderson *et al.* 1991a,b; Evans *et al.* 1992, 1993; Derbyshire *et al.* 1996; Sudiyani *et al.* 2003; Williams 2005; Evans *et al.* 2008; Monteiro Pastore *et al.* 2008; Ganne-Chedeville *et al.* 2012; Huang *et al.* 2012a; Jelle *et al.* 2012; Kocaefe *et al.* 2013; Gupta *et al.* 2015; Jankowska *et al.* 2017; Liu *et al.* 2017; Reinprecht *et al.* 2018a; Han *et al.* 2019
Hemicelluloses (decreases near to the surface)	Evans *et al*. 1992; Sudiyani *et al.* 2003; Ganne-Chedeville *et al.* 2012; Jelle *et al.* 2012; Lionetto *et al.* 2012; Jankowska *et al.* 2017; Han *et al.* 2019
Cellulose (increases near surface)	Lionetto *et al.* 2012; Almeida *et al.* 2019b

Though it would be reasonable to expect that weathering of wood's surface would seriously decrease overall strength properties, research findings have not shown a completely consistent trend. For instance, Cavalli *et al.* (2016) noted instances where natural weathering resulted in increases in certain strength attributes. Certain ancient wood specimens, for which the exposure to weather is often not fully known, have remained structurally sound with only modest strength losses in comparison to modern wood of the same types (Chowdhury *et al.* 1967). Tests focusing on the strength of outermost layers generally have detected the greatest relative decreases in strength (Derbyshire *et al.* 1996).

Chemical changes are generally consistent with a loss of lignin and hemicelluloses near to the wood surface. By contrast, cellulose appears to be relatively resistant to natural weathering, though its crystallinity and crystal size may increase (Lionetto *et al.* 2012; Almeida *et al.* 2019b). The increase of crystallite size can be interpreted as a loss of non-crystalline cellulose and coalescence between adjacent cellulose fibrils (Pönni *et al.* 2012). It should be noted, however, that a loss of crystallinity of cellulose has been reported in the case of ancient wood stored under generally dry, dark conditions (Nilsson and Daniel 1989).

As a general rule, weathering tends to render wood more wettable by water (Williams 2005). However, as noted by Kishino and Nakano (2004a,b), sometimes the initial effect is the opposite, showing increases in hydrophobicity. Regarding chemical changes, the weathered layer of wood has been found to contain less lignin and less hemicellulose. Such findings were reported, uniformly, by the authors listed in Table 5 associated with the terms "lignin" and "hemicellulose". By contrast, cellulose appears to be relatively resistant to natural weathering, though its crystallinity and crystal size may increase (Lionetto *et al.* 2012; Almeida *et al.* 2019b). The increase of crystallite size can be interpreted as a loss of non-crystalline cellulose and coalescence between adjacent cellulose fibrils (Pönni *et al.* 2012).

Effects of Site Conditions

Before considering the mechanisms associated with wood weathering, various studies have shown effects of conditions at the site of natural weathering. Results from such studies are summarized in Table 6.

Delucis *et al.* (2016) observed that wood weathered in a forest environment was less changed in comparison to wood weathered in an open environment. The effects were attributed to the insulation provided by the trees. Other issues, such as the amount of sun exposure, also could contribute.

Table 6. Effects of Site Conditions on Natural Weathering

Reported Change	Selected Citations
Climatic differences	Delucis *et al.* 2016
Position relative to the sun	Sandberg 1999; Williams *et al.* 2001a,b; Sandberg & Söderström 2006; Liu *et al.* 2017;
Position relative to drainage	Ruther & Jelle 2013
Air pollution effects	Reinprecht *et al.* 2018a
Dry aging	Kudela & Ihracky 2014; Cavalli *et al.* 2016; Kranitz *et al.* 2016; Matsuo *et al.* 2016; Obataya 2017; Zeniya *et al.* 2019

Regarding the orientation of the exposed wood surface relative to the prevailing sunlight, Liu *et al.* (2017) found that weathering-induced changes in color were greatest on the tangential surfaces, followed by the cross surfaces (end-grain), and least on the radial surfaces. Williams *et al.* (2001a,b) observed higher erosion on the surface of vertical-grained plywood in comparison to flat-grained plywood. The position of the wood also influences the ability of rain to drain from an exposed surface; Ruther and Jelle (2013) observed that horizontally mounted wood experienced higher mold growth compared to vertically mounted boards.

Dry conditions, in general, have been observed to result in much lower changes in the attributes of exposed wood. In particular, Kudela and Ihracky (2014) conducted parallel tests, contrasting water-free exposure to UV radiation with and without intermittent wetting. The water-free treated specimens showed only minor morphological changes, whereas the specimens that had been exposed to water become rougher. Obataya (2017) reported a long-term decrease in the hygroscopic nature of wood. The effects were attributed to the annealing-like rearrangement of amorphous polymers in the wood, as well as closure of submicroscopic pores.

The importance of water with respect to the achievement of a gray, weathered appearance is also made evident in recommendations from the Plywood Association (Feist 1982). The situation considered was when the goal of a property owner is to achieve a similar degree of weathered appearance on different sides of a building. The challenge lies in the fact that some sides of a house receive less sunlight than other sides, and also the moisture levels may differ. The recommendation was essentially to speed up the weathering process by periodically spraying water onto those sides of the building presently exhibiting the least changes from the original wood's appearance.

Mechanisms

This section considers published work that helps explain typical changes that are brought about by weathering. The topic areas are grouped as effects of ultraviolet (UV) light, other chemical processes, leaching, moisture cycles, and biological effects.

Effects of UV light

Ultraviolet light appears to play a central role in the natural weathering of wood. This is despite the fact that most of the UV rays from the sun, especially at shorter wavelengths, are absorbed by the ozone layer in the outer atmosphere (Desai 1968). As shown by Lean *et al.* (1997), measurable amounts of UV irradiation can be detected on the Earth's surface at wavelengths as low as 210 nm. Though solar radiation goes through cycles having about a 10-year period, there is a roughly linear increase in radiant intensity between near zero at 250 nm wavelength to a higher value at about 450 nm, which is in the blue region. Shorter-wavelength UV light is more energetic, but it is less abundant. As noted by Derbyshire and Miller (1981) and Derbyshire *et al.* (1996), a given dosage of shorter-wavelength UV light can be expected to create more damage to wood. This concept was supported by the work of Evans *et al.* (2008), who found that there was substantially less change to wood surfaces that were exposed to sunlight in which the shorter UV light rays (UV B – 260 to 345 nm) were blocked by a filter. By contrast, Kataoka *et al.* (2007) found no detectable change in wood following irradiation by blue light (434 to 496 nm), despite the ready ability of such light to penetrate relatively deep into wood.

In order for a photon of UV light to bring about a chemical change, its energy must at least be sufficient to raise one of the electrons in a compound from its baseline energy level to a higher level, thus enabling the breaking or forming of chemical bonds (Wayne 1996). Lignin is known to absorb UV light strongly at about 280 nm (Koch and Kleist 2001; Luo *et al.* 2009), and there is also a maximum of absorbance near to 400 nm, at the blue edge of the visible light range (Kline *et al.* 2010). Lignin also has been shown to be highly effective as an UV light absorber in sunscreen (Qian *et al.* 2015). However, what makes lignin highly effective for short-term protection of skin, *i.e.*, its ability to absorb UV light, renders it susceptible to long-term decomposition. Tondi *et al.* (2013) noted that tannins exhibit a similar vulnerability toward UV light, similar to that of lignin; though the tannin can protect wood for a while by absorbing the UV light, it will eventually break down. Williams (2005) discussed certain functional groups within lignin that would be able to absorb light in the range 295 to 400 nm, giving rise to activated species that might participate in further degradative reactions. Table 7 lists various studies indicating a central role of ultraviolet light in the decomposition of lignin at weathered wood surfaces.

Table 7. Reported Findings Related to Ultraviolet Light and Exposed Wood Surfaces

Reported Change	Selected Citations
Lignin is susceptible to breakdown when irradiated by UV light.	Feist 1982; Hon & Feist 1986; Evans *et al.* 1993; Derbyshire *et al.* 1996; Wang *et al.* 1998; Sudiyani *et al.* 2003; Kishino & Nakano 2004a,b; Williams 2005; Temiz *et al.* 2007; Evans *et al.* 2008; Monteiro Pastore 2008; Ganne-Chedeville 2012; Kocaefe *et al.* 2013; Yildiz *et al.* 2013; Gupta *et al.* 2015; Poletto 2017; Cogulet *et al.* 2018; Reinprecht *et al.* 2018a
Free radicals are generated when UV light is absorbed by wood.	Philips *et al.* 1966; Hon & Ifju 1978; Feist 1982; Hon & Feist 1982, 1986; Feist & Hon 1984; Williams 2005
Photo-oxidation reactions are initiated following exposure to UV light.	Browne & Simonson 1957; Forest Products Laboratory 1966; Desai 1970; Feist & Rowell 1982; Hon & Feist 1982, 1986, 1992; Feist & Hon 1984; Nilsson & Daniel 1989; Jirous-Rajkovic *et al.* 2004b; Salaita *et al.* 2008; Matsuo *et al.* 2011; Ganne-Chedeville 2012; Liu *et al.* 2016, 2017; Jankowska 2017; Poletto 2017; Cogulet *et al.* 2018
Compounds are formed in photo-oxidation reactions.	Desai 1968; Feist & Hon 1984; Hon & Feist 1986
Condensation reactions follow exposure to UV light.	Schabel & Huber 2014
Loss of molecular mass of cellulose occurs.	Desai 1970.
UV light has limited depth of penetration into wood.	Browne & Simonson 1957; Hon & Ifju 1978; Feist 1982; Williams 2005; Zivkovic *et al.* 2016; Kataoka *et al.* 2007

As noted in the table, the connection between UV irradiation and the deposition or eventual loss of lignin from wood's surface has been reported by many studies. For instance, Emmanuel *et al.* (2015) noted a relative increase on –OH groups in the outer portions of weather-exposed wood; though the cited authors attributed this to diffusion of chemical species having –OH groups, the results are consistent with depletion of hydroxyl-poor lignin species from the surface.

Important progress has been achieved, relative to the mechanism of lignin degradation, when using electron spin resonance (ESR) spectrometry (Kleinert 1965; Phillips *et al.* 1966; Hon and Ifju 1978; Hon and Feist 1982; Feist and Hon 1984). The ESR method is able to quantify the levels of free radicals that are generated in a material, *e.g.*, when wood is exposed to UV light. As discussed by Williams (2005), it is reasonable to expect that the free radicals, once generated, may migrate or be transmitted by means or chemical transformations, to bring about chemical changes somewhat deeper within the wood structure. While most attention has been directed towards the absorption of UV light by lignin, Phillips *et al.* (1966) examined purified cotton cellulose and detected a broad absorbance in the range 325 to 400 nm. Absorption in that range gave rise to ESR signals, indicating the presence of free-radical species.

As noted earlier, many authors have reported that most weathered wood, even after extensive exposure, has a photobleached or gray layer that is only 2 to 5 mm thick (Forest Products Laboratory 1966; Sell 1968; Feist 1982; Han *et al.* 2019). As noted in the final item in Table 7, the thinness of weathering effects has been widely attributed to the limited penetration of UV light into wood. A problem with this explanation is that some of the critical experiments were done with fresh wood specimens (Browne and Simonson 1957). Results of such tests can be regarded as inconclusive, since the lignin present in the fresh wood is known to absorb UV light strongly. After long exposure, the lignin near the surface would have become photochemically degraded and therefore not able to perform its role in absorbing UV light. This means that there is a need for a more complete explanation.

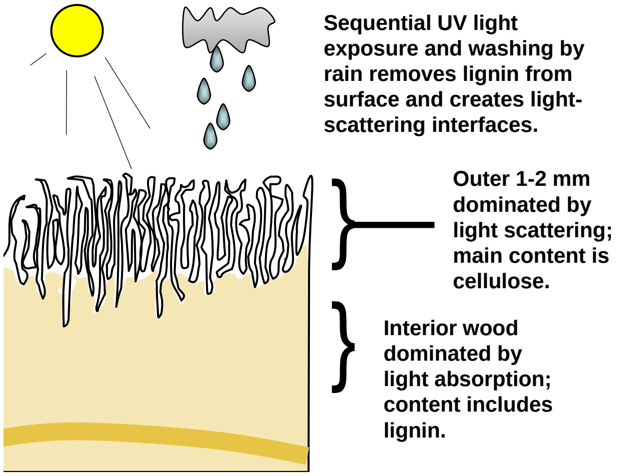
According to the Kubelka-Munk model, the ability of light of a given wavelength to penetrate into a material can be related to two quantities, a light absorption coefficient K and a light scattering coefficient S (Kubelka and Munk 1931; Roy *et al.* 2012). The relationship between light transmission T through a material and the corresponding values of S and K are shown in Eq. 1, where t represents the thickness of the material,

$$T = \frac{4\beta}{(1+\beta)^2 \exp(\alpha t) - (1-\beta)^2 \exp(-\alpha t)} \tag{1}$$

where

$$\alpha = [K(K+2S)]^{0.5} \quad \text{and} \quad \beta = [K/(K+2S)]^{0.5}$$

The surface layer of fresh wood, due to the presence of lignin, is expected to absorb light strongly, giving a relatively high value of K, but that ability is expected to decline as the lignin is degraded and removed from the surface layers. By contrast, the ability of a material to scatter light is highly dependent on the presence of interfaces between solid phases and air. Such abrupt changes in refractive index result in the scattering of light (Alince *et al.* 2002). The porous, friable nature of the surface of weathered wood (Browne and Simonson 1957; Feist 1982; Nilsson and Daniel 1989; Xiao 2012; Hazneza and Evans 2016) is thus well suited for the efficient scattering of light due to the very high number of transitions between solid phases and air spaces as a light beam progresses into the material. Accordingly, it is proposed here that the mechanism by which the penetration of UV light into wood can be expected to shift from more absorption-dependent to more scattering-dependent over the course of time. The mechanism is shown schematically in Fig. 7. The proposed mechanism also is consistent with the widespread usage of high-light-scattering minerals such as TiO_2 particles for the protection of wood from UV exposure (Miklecic *et al.* 2017; Panek *et al.* 2017).


Sequential UV light exposure and washing by rain removes lignin from surface and creates light-scattering interfaces.

Outer 1-2 mm dominated by light scattering; main content is cellulose.

Interior wood dominated by light absorption; content includes lignin.

Fig. 7. Schematic description of mechanism by which enhanced light scattering in a lignin-depleted, friable surface layer (1 to 2 mm) of weathered wood can protect the underlying lignin-containing wood from exposure to UV light. The curved tan line low in the drawing is meant to suggest an annual ring (latewood).

Other chemical processes

Although degradation of lignin clearly plays a key role with respect to the breakdown of cohesion between fibers, destruction of bordered pits, and development of cracks in the surface of outdoor-exposed wood, other chemical processes must also be involved. Whereas lignin is vulnerable to UV light, the polysaccharides, especially the hemicelluloses, can be expected to be vulnerable to acid-catalyzed hydrolysis reactions (Feist 1982; Nilsson and Daniel 1989). Acid treatment also has been found to accelerate the effects of subsequent weathering (Williams 2005). Williams (1988a,b) observed the fastest erosion of wood during weathering after it had been treated with a solution of sulfurous acid, which was compared with several other acids. Such results are consistent with the process of acid sulfite pulping, which is well known to be effective for degrading the material holding fibers to each other in wood. Deppe and Schmidt (1991), who employed solutions of acids in an effort to simulate effects of air pollution, likewise observed faster changes in the mechanical properties of wood.

Leaching

Many researchers have reported that weathering effects tend to be much greater when exposure to sunlight or UV irradiation is accompanied by periodic rain or water spray (Forest Products Laboratory 1966; Feist 1982; Anderson *et al.* 1991a,b). It appears that periodic exposure to water serves the role of leaching out degraded wood byproducts that had been rendered soluble by light-induced reactions (Liu *et al.* 2017; Panek *et al.* 2017). Table 8 lists some of the most widely reported aspects related to the role of water exposure during the weathering of wood.

Table 8. Reported Findings Related to the Role of Water during the Weathering of Wood

Reported Change	**Selected Citations**
Loss of matrix materials (lignin and hemicellulose) near the wood's surface	Wiesner 1864; Williams 2005; Salaita *et al.* 2008; Jelle *et al.* 2012; Teles & da Costa 2014; Kanbayashi *et al.* 2018
Solubilization of wood decomposition products	Forest Products Laboratory 1966; Evans *et al.* 1992; Feist 1982; Feist & Rowell 1982
Middle lamella loss or weakening	Borgin 1970; Hon & Feist 1986; Nilsson & Daniel 1989; Evans *et al.* 2000, 2008
Lignin loss specifically	Evans *et al.* 1992; Ganne-Chedeville *et al.* 2012; Yildiz *et al.* 2013
Hemicellulose loss	Feist 1982; Williams 1988; Evans *et al.* 1992; Tolvaj & Faix 1995; Ganne-Chedeville *et al.* 2012; Lionetto *et al.* 2012; Yildiz *et al.* 2011, 2013; Schnabel & Huber 2014
Protective effects of hydrophobic coatings	Forest Products Laboratory 1966; Sell 1968; Borgin and Corbett 1970; Dunningham *et al.* 1992; Kabir *et al.* 1992; Evans *et al.* 2000; Dawson *et al.* 2005; Temiz *et al.* 2007; Evans *et al.* 2008; Ozgenc *et al.* 2013; Panek & Reinprecht 2014, 2016a,b; Saei *et al.* 2015; Turkoglu *et al.* 2015a,b; Ozgenc & Yildiz 2016; Sivrikaya & Can 2016; Zlahtic & Humar 2016, 2017; Ozgenc 2017; Panek *et al.* 2017; Sivrikaya *et al.* 2017; Cogulet *et al.* 2018; Oberhofnerová *et al.* 2018; Reinprecht *et al.* 2018b

Findings related to the wholesale loss of the middle lamella, *i.e.* the material that in sound wood attaches adjacent fibers to each other, can be viewed as evidence of lignin degradation and subsequent solubilization and leaching by water. Such an interpretation follows from the fact that lignin often makes up about 34 to 85% of the substance of the middle lamella (Fengel and Wegener 1983).

Relative to loss of hemicellulose from weathered layers of wood, Feist (1982) noted that xylan and araban moieties, which are hemicellulose monomeric components, tend to be lost to a much greater extent than glucan moieties during weathering. Though there are some glucose units in certain types of hemicellulose, the great majority of glucose units within wood are associated with cellulose (Fengel and Wegener 1983). Yildiz *et al.* (2011) observed that heat-treated alder wood was especially susceptible to the leaching of hemicellulose byproducts from the surface layers during weathering.

The last item in Table 8, having to do with hydrophobic coatings, pertains to studies in which specimens were exposed to the usual aspects of weathering, but the surface was covered with either a clear solid coat (*e.g.* a varnish) or with an oil or wax. Such coatings, due to their nature, would not block any of the radiation, so the protective effects have to be attributed to their ability to keep the surfaces dry.

Moisture cycles

In addition to its importance in terms of leaching solubilized materials from outer layers of wood during weathering, cycles of wetting and drying appear to be very important to the development of cracks and checks at the wood surface. It is well known that wood has slightly larger dimensions when in a completely wet state compared to when it is in full equilibrium with ambient air, *i.e.*, “dry”. For instance, Naderi and Hernandez (1997) found that maple wood swelled by 2.0 to 2.2% in its radial direction and 5.1 to 5.4% in its tangential direction when placed into water.

High stresses can develop near the surface of wood when a wet board begins to dry rapidly on one side, as in the case of a board exposed to full sun and dry weather right after a rain (McMillen 1955; Schniewind 1963; Feist 1982; Feist and Hon 1984; Evans *et al.* 2008). This mechanism is illustrated schematically in Fig. 8, where the upper part of the figure represents the condition soon after the rains had stopped.

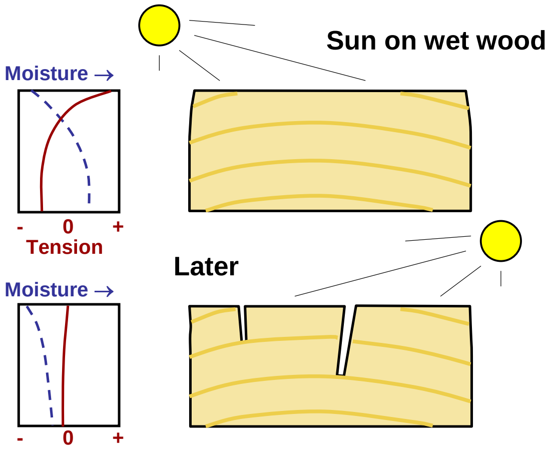


Fig. 8. Schematic diagram of a likely mechanism leading to formation of checks when wet wood begins to dry at the surface. Moisture increases from left to right (purple curve). Tension (red curve) is zero at the midpoint of the horizontal axis. A moderate shrinking is depicted as a way to emphasize the presence of tension within the wood, especially near its exposed surface at the start of the drying cycle.

Surface drying can be expected to induce a tendency of shrinkage and buildup of stress, especially in the annual rings nearest to the board's tangential surface. The figure depicts a possible formation of checks, the depth of which may or may not correspond to annual rings. Such a mechanism, along with the information given above about changes in dimensions during wetting and drying, can help to explain why checking tends to be most frequent, with the deepest crack forming on tangential surfaces of a board, rather than on radial surfaces (Sandberg 1999).

In addition to checks formed as a result of wood weathering, related defects may also be produced by mechanical stresses during planing of wood. As shown by Ohya *et al.* (1992, 1993), the development of such purely mechanical-induced checks depends on such factors as the vertical load during planing, the loading angle, the rate of strain release, and the wood's ability to resist tensile forces.

Table 9 summarizes some of the main effects related to checking, along with a listing of sources for the reported observations.

Table 9. Reported Findings Related to Cycles of Wetting and Drying, Leading to Check Formation during the Weathering of Wood

Reported Change	**Selected Citations**
Developments of checking in general	Feist & Rowell 1982
Requirement for water to be present in weathering to generate checking	Borin & Corbitt 1970; Dunningham *et al.* 1993; Jebrane *et al.* 2017
Requirement for UV irradiation in weathering to generate checking	Evans *et al.* 2008; Huang *et al.* 2012a
Development of microscopic checks	Miniutti 1964; Panek *et al.* 2017
Degradation of bordered pits leading to development of micro-checking	Dunningham *et al.* 1993; Evans *et al.* 1994; Williams 2005
Rays in wood as the site of initiation of checking	Schniewind 1963; Wang & Youngs 1996; Evans *et al.* 2008
Middle lamella as the site of initiation of micro-checks	Miniutti 1964
Microfibril angle within a fiber as the site of initiation of micro-checks	Miniutti 1964; Williams 2005
Checking initiated at the earlywood-latewood border	Williams 2005
Development of relatively large checks	Evans *et al.* 2008
Deeper and more frequent checks on tangential surfaces of exposed wood	Sandberg 1999
Freeze-thaw cycles possibly contributing to checking	Feist & Hon 1984
Checks initiated by fungal decay and leading to decay	Adamopoulos *et al.* 2011; Osawa *et al.* 2019

Biological effects

In addition to solar radiation and rainfall, a third major factor affecting the appearance of weathered wood falls into the category of biology (Duncan 1963; Feist 1982; Zabel and Morrell 1992; Cogulet *et al.* 2018). In particular, colonization of the surface of wood by bluestain fungi, *e.g.*, *Aureobasidium pullulans* and *Sclerophoma pithyophila*, contributes to a blue-gray shade of typical weathered wood (Humar *et al.* 2008). The effect of bluestain colonization can be appreciated when one notes the silvery shade of weathered wood that has been observed at seaside locations (Forest Products Laboratory 1966). The explanation given was that wind-blown salty spray might have prevented fungal growth. Another main biological contributor to color is mold (Browne and Simonson 1957; Zabel and Morell 1992; Ruther and Jelle 2013; Oberhofnerová *et al.* 2017; Reinprecht *et al.* 2018b). According to Zabel and Morell (1992), molds and their effects are mainly limited to very wet wood specimens.

Two main routes for transportation of stain fungi to the surfaces of wood appear to be wind and insects, especially beetles (Zabel and Morrell 1992). Once present, the stain fungal organisms extend root-like microscopic hyphae into openings in the wood surface, *e.g.*, cracks, lumens, and vessels in various types of wood. Bluestain colonization is typically isolated near to the surface. According to Sell (1968), bluestain organisms seldom go deeper into the wood than 1 mm. In other cases, discoloration by bluestain hyphae has been observed deep within weathered wood, basically affecting the wood's bulk coloration (Uzunovic *et al.* 2008). However, it has been reported that bluestain colonization often has minimal or no measurable effect on bulk properties of the wood (Humar *et al.* 2008).

Key findings relative to biological effects during ordinary weathering of wood are listed in Table 10, along with citations. Two key requirements for the development of fungal or other decay-related microbial attack are moisture and a source of food. According to Sell (1968), the moistening at least needs to exceed the fiber saturation point of the wood. In the case of wood weathering, the food can be provided by storage carbohydrates, such as starch, which generally can be found in the parenchyma cells within wood (Zabel and Morrell 1992). The requirement of moisture can provide challenges to biological organisms because episodes of rain, dew, *etc.*, are often interrupted by extended periods of dry weather, during which the wood surface is expected to dry out completely.

Table 10. Reported Findings Related to Biological Effects during the Weathering of Wood

Reported Change	**Selected Citations**
Bluestain fungal colonization	Forest Products Laboratory 1966; Sell 1968; Arndt & Willeitner 1969; Feist 1982; Zabel and Morrell 1992; Goodell *et al.* 2006; Humar *et al.* 2008; Uzunovic *et al.* 2008; Adamopoulos *et al.* 2011; Ruther and Jelle 2013; Jebrane *et al.* 2017; Zlahtic and Humar 2017; Kržišnik *et al.* 2018
Enzymatic discoloration and degradation	Sell 1968; Uzunovic *et al.* 2008
Protection by fungicides	Sell 1968; Rolf 1980; Evans *et al.* 1992, 1994; Gascon-Garrido *et al.* 2017; Sivrikaya *et al.* 2017
Protection against fungi by hydrophobic oils	Ozgenc and Yildiz 2014; Oberhofnerová *et al.* 2018; Reinprecht *et al.* 2018b
Rotting of wood facilitated by previous weathering	Arndt and Willeitner 1969
Insect effects in wood	Nilsson and Daniel 1989; Zabel and Morrell 1992

As described by Feist (1982), the wet conditions may be “sporadic”. It appears that bluestain fungi deal with the challenge of periods of very dry weather by creating spores, which serve as a starting point for regrowth when wet weather conditions return. In fact, some researchers have attributed the blue-gray color of weathered wood at least in part to the color of the fungal spores (Browne and Simonson 1957; Forest Products Laboratory 1966; Zabel and Morrell 1992; Uzunovic *et al.* 2008). Other researchers have suggested that a main contribution of bluestain fungi to the color of weathered wood is due to the fungal hyphae (Arndt and Willeitner 1969; Zabel and Morrell 1992; Uzunovic *et al.* 2008). According to Zabel and Morrell, the coloration within hyphae sometimes develops 5 to 6 days after hyphal extension, which can give the impression of sudden graying.

ACCELERATED WEATHERING

Motivations for Use of Accelerated Weathering Tests

There are three main reasons to employ artificial weathering conditions, and these can be called prediction, understanding, and reproducibility. Prediction is important when answers about weathering – or its avoidance – are wanted relatively quickly. For example, a company may be developing new varieties of clear coatings for wood, and they would like to make decisions about which formulation to use next month rather than three years from now. Accelerated weathering eliminates idle times, at which the material is not stressed, altered, or simply aged (Grossmann 1977). Matejak *et al.* (1983) reference the 1953 version of the Wood Handbook, estimating the time for full deterioration of a 6 mm wood layer at 100 years. Arnold *et al.* (1991) estimate an acceleration of natural weathering by 5 to 20 times. Our understanding of how the weathering process works has benefitted greatly from the carrying out of experiments in which certain factors, such as the presence of water, can be selectively excluded from a treatment. The reproducibility of the experimental results is expected to be easier to obtain in the laboratory than in a chaotic out-of-doors environment. Table 11 shows some of the publications that have shed light on key motivations for artificial weathering of wood.

Table 11. Key Motivations to Consider Artificial Weathering of Wood

Motivation	**Selected Citations**
Achieve results that accurately match those of natural weathering.	Lyon & Fron 1929; Deppe & Schmidt 1979, 1991; Hon & Feist 1986; River 1994; Podgorski *et al.* 1996; Jirous-Rajkovic *et al.* 2004a; Kojima & Suzuki 2011a,b; Reinprecht & Panek 2013, 2015; Ruther & Jelle 2013; Grüll *et al.* 2014; Gupta *et al.* 2015; Panek & Reinprecht 2016a; Herrera *et al.* 2018; Kržišnik *et al.* 2018; Reinprecht *et al.* 2018a; Almeida *et al.* 2019a; Liu *et al.* 2019
Achieve higher precision in the results of weathering.	Arnold *et al.* 1991
Keep the tests as simple as is practical without losing validity in the predictions.	Back & Sandström 1982; McNatt & McDonald 1993

Table 12 lists the types of equipment and underlying conditions of different artificial weathering projects that have used UV-light during the treatment. The relative humidity varies moderately; however, it leaps to the eye that the black panel temperature is above 60 °C in most cases. Black-panel refers to the black coating of the temperature sensor that is supposed to absorb light at all wavelengths and provide the theoretical maximum temperature of tested materials. These temperatures exceed the habitable range of microorganisms. Thus, artificial weathering protocols generally do not consider effects due to bluestain or mold growth.

Table 12. UV-Light, Parameters, and Duration of Exposure

UV Light	Temperature and Relative Humidity	Exposure, Duration and Total Time	Test	Source
Exposure 1: UVA-340 Exposure 2: Xenon (borosilicate filter)	Exposure 1: 60 °C Exposure 2: 50 °C	Exposure 1: light 5h, spray 1h Exposure 2: light 24h, spray 4h	Erosion	Arnold *et al.* 1991
Xenon, 6500 W	45 °C to 50 °C, 50%	Set 1: 24 h light only; Set 2: 4 h spray, 20 h UV, total 600, 1200, & 1800 h	Erosion	Feist 1982
Atlas MTT, Xenon, 180 W/m^2, 300 to 400 nm	65 °C (black panel), 50%	Total: 180 h	CIELab, ATR-FTIR	Liu *et al.* 2019
Hanau Suntest, Xenon, sunlight spectra filter		Total: 200	CIELab	Papp *et al.* 2012
QUV accelerated weathering tester, UVA-340 lamp, 365 to 195 nm, peak at 340 nm		2.5 h UV, 30-minute spray, 7 to 208 cycles		Petrillo *et al.* 2019
Atlas Ci4000, Xenon, 0.51 W/m^2 at 340 nm	65 °C (black panel)	18-minute spray every 2 hours, total: 500 h, w/o spray	Surface chemistry	Kanbayashi *et al.* 2018
Suga Test Instrument sunshine xenon WEL-6XS-HC-Bec-S, Xenon, quartz glass filter (300 to 700 nm), 390 Wm^{-2}	65 °C (black panel)	120-minute cycle; 18-minute spray Total: 600 h	Contact angle, FTIR, Light Microscope	Kishino & Nakano 2004a Part 1
Atlas Suntest XXL+, three 1700 W xenon lamps, 300 – 420 nm, EN 16474-1, 0.35 $W\ m^{-2}$ (340nm),	63 °C (black panel) Dry cycle: 40% to 60%	2 h cycle, 102-minute dry phase, 18 min spray, total 500 h	CIELab	Kržišnik *et al.* 2018
Xenotest Q-SUN Xe-3-HS, 0.35 W/m^2, 63 °C (black panel), 48 °C, 30% RH	63 °C (black panel), 30 % and 90 %	102 minutes, 18-minute spray, total: 600 h	Surface roughness	Kudela & Ihracky 2014
QUV accelerated weathering tester, UVA-340 lamp, 0.85 W/m^2 at 310 nm, 50 °C		2 h light, 18-minute spray, total: 1000 h		Nzokou *et al.* 2011
QUV accelerated weathering tester, 0.85 W/m^2 at 340 nm		2 h light, 18-minute spray, total: 2400 h		Nzokou & Kamdem 2006
Hanau, F.R.G., wide range mercury vapor light, without filter (300W)	45 specimen temperature, 50 %	Total: 200 h	Color	Tolvaj & Faix 1995

Ruther and Jelle (2013) reported relatively poor agreement of the results from natural and artificial aging tests, and they attributed the poor agreement to biological activity in the naturally aged specimens. However, the general message from most of the other studies has been that natural and artificial weathering generally result in similar changes in properties.

Artificial Weathering Factors

Common factors that define and characterize artificial weathering treatments include UV-light irradiation, temperature, water spray and humidity, duration and intensity, and the number of repeated cycles. Different factors that have been studied using artificial weathering are shown in Table 13. The list of factors reveals that artificial weathering treatments can be more complex than simply combining moisture and UV radiation into a weathering treatment. Other factors that affect the exposure in natural environments, such as air pollution and seasonal differences, as well as material-related impacts, complicate the design of artificial weathering treatments.

Table 13. Key Factors that Have Been Studied Using Artificial Weathering of Wood

Factors Considered	Selected Citations
UV light attributes	Hon & Feist 1986
Presence or absence of wetting	Feist & Rowell 1982; Arnold *et al.* 1991; Kudela & Ihracky 2014; Kanbayashi *et al.* 2018
Air pollution	Lyon & Fron 1929
Simulated seasons of weather	Deppe & Schmidt 1979
Mild weathering conditions	Schmidt & Deppe 1996; Saad *et al.* 2016
Freezing events	Matejak *et al.* 1983
Type or composition of wood	Kishino & Nakano 2004b; Monteiro Pastore *et al.* 2008; Barreto & Pastorez 2009; Liu *et al.* 2017
Effects of wood extractives	Nzokou & Kamdem 2006; Shen *et al.* 2016
Effects on wettability	Kishino & Nakano 2004a

UV Light

Three types of UV radiation can be distinguished based on their wavelength ranges: UV-A (315 to 400 nm), UV-B (280 to 315 nm), and UV-C (200 to 280 nm) (Nikafshar *et al.* 2017). Three types of lamps commonly used are mercury vapor, xenon, and fluorescent light bulbs. Mercury vapor lamps use an electric arc that is passed through vaporized mercury. Xenon arc lamps generate UV light by passing electricity through xenon gas. Best practices for the operation of such lamps for weathering of non-metallic materials are given by ASTM G155 (2013): Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials. According to this standard, daylight simulation with xenon arc lamps requires the use of daylight filters to reduce the irradiance at short UV wavelengths. Furthermore, the standard recommends the removal of wavelengths below 310 nm to simulate the exposure through window glass. Too much radiant energy below 300 nm is mentioned to accelerate test results; however, some of these weathering processes might not naturally occur. UV-C light is naturally absorbed by the atmosphere and therefore is not part of natural light. An extended UV filter can be used as a bandpass filter to allow specific wavelengths. Fluorescent light bulbs produce UV light by combining the effects of electrically excited mercury vapor and an exterior phosphor coating. Their operation is defined by ASTM 154-16 (2016): Standard Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials. The standard lists UVA-340, UVA-351, and UVB-313 as the most common fluorescent UV lamps. UVA-340 has a peak emission at a wavelength of 343 nm and is used for simulated daylight exposure. UVA-351 has a peak emission at a wavelength of 350 nm and is used to simulate daylight exposure through window glass. UVB-313 lamps peak at 313 nm and a larger portion of its light is emitted below 320 nm.

ASTM G154-16 (2016) provides different examples of UV exposure conditions. Examples are given for different lamp types and irradiance levels. UV exposure periods are suggested to be between 4 and 20 hours, with 8 hours being the most common. Light exposure is then followed by a high moisture phase or water spray. The suggested duration is 4 hours, whereas a 15-minute spray reduces that time to 3 hours and 45 minutes. The standard recognizes temperature as an essential factor to accelerate weathering effects. The black panel temperature during UV exposure is between 60 and 80 °C and at 50 °C during condensation. Temperature is typically not controlled during water spraying.

Nzokou and Kamdem (2006), Nzokou *et al.* (2011), and Petrillo (2019), have used the Q-LAB QUV device in their studies that used fluorescent UVA light bulbs. Nzokou *et al.* (2011) used 2 hours of UVA-340 light bulbs and 18 minutes of water spray for an initial cycle and UV for a subsequent cycle of light only. Each cycle took 1000 hours. In another experiment, Nzokou and Kamdem (2006) exposed specimens to the same types of UV and spray for a total of 2400 hours.

Water Spray and Humidity

Many wood properties are influenced by the interaction between wood, which is a hygroscopic material, and moisture (Ross 2010). Periodic water spray increases the dynamics of the weathering processes. As shown in Table 13, Kishino (2004a,b), Kudela (2014), Kržišnik (2018), and Nzokou and coworkers (2011, 2006) used some type of water spray during the exposure. In their 2004 study, Kishino examined the changes in the wettability of eight tropical wood species before and after artificial weathering. The authors concluded that changes in wettability could be mostly explained by a combination of chemical and structural changes of the wood substance. Based on their observations, the contact angle, a measure for wettability, is inversely related to the area, length, and width of surface cracks. Kudela (2014) exposed beech (*Fagus sylvatica* L.) to two different weathering schedules, water-free and wet, following ASTM G155 (2013). Changes in surface roughness were noticeably larger after the latter and in some cases negligible after the former. Cyclic changes in moisture content along the sorption isotherms below fiber saturation, create surface stresses and promote the moisture-induced formation of cracks (Matejak 1983). Dimensional changes of wood only occur below the fiber saturation point, which is typically at 30 % moisture content (Ross, 2010).

Periodic exposure to heat, relative humidity, and radiation cause the wood to continually swell and shrink (Deppe 1979). The greater or more rapid the change in moisture content, the more likely are structural changes in the wood. Based on the *Wood Handbook* (Ross 2010), the change from 30 to 90% RH at 60 °C in ASTM G 155 alternates the equilibrium moisture content between 5.0 and 17.7%. The use of water spray in accelerated weathering is often thought to simulate the exposure to rain (Kishino 2004a). Changes to the surface chemistry are caused by a combination of photodegradation and leaching mechanisms, which results in a washing out of extractives, low molecular weight degradation products, and inorganic compounds. The accelerating effect of water was also observed by Kanbayashi *et al.* (2018). The assessment of weathered specimens of Japanese cedar (*Cryptomeria japonica* D. Don) using confocal Raman microscopy revealed that degradation in the presence of water occurs on the exposed surface and inside of the lumen. This observation was consistent with results reported by Feist and Rowan (1982). In their study, weight loss was 2 to 11 times greater after an exposure that included water spray compared to UV radiation only. In a 1991 study, Arnold *et al.* concluded that whatever UV light is used, the water spray is essential to remove degraded material and complete the weathering process.

In the presence of water, freezing can further accelerate the weathering processes. In a study conducted by Matejak *et al.* (1983) a comparison between short and extended treatments, of which the latter included 12 hours of freezing and 12 hours of UV, showed a higher decrease in mechanical compression strength for the extended treatment. Tests were conducted on pine sapwood specimens. It was found that the shorter cycle was only 70% as effective as the extended treatment.

Hydrothermal Treatments

Hydrothermal treatments combine the effects of temperature and moisture. The durability of wood-based composites is typically assessed using ASTM D1037 (2012), Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials. Section 7, accelerated aging, contains the ASTM six-cycle treatment. Table 14 provides an overview of the sequence of steps. With temperatures close to the boiling point of water, specimens are exposed to several steps of hydrothermal treatments using steam and water vapor.

In addition to the ASTM six-cycle, other accelerated weathering standards exist to assess and compare the performance of wood products. A study by Kojima *et al.* (2009) compared the effects on tensile strength of five common accelerated weathering treatments to specimens of the same panel after two years of outdoor exposure in Shizuoka City. A single ASTM six-cycle was found to be more severe than 2 years of outdoor exposure based on tensile strength. The project was continued, and a comparison of internal bond strength was conducted for 5 years of outdoor exposure (Kojima and Suzuki 2011a). It was observed that 3 ASTM six-cycle treatments correspond to 5 years of outdoor exposure. Compared to other treatments, such as V313 (EN 321 2002), APA D-1 (APA 1994), vacuum-pressure-soak-dry (VPSD), and JIS-B (Japanese Standard Association 2003), the latter and the ASTM six-cycle were among the most severe treatments. For bending tests of the same specimens, the authors observed a close one-to-one correspondence between outdoor exposure and the JIS-B, APA D-1, and ASTM six-cycle treatment (Kojima and Suzuki 2011b).

Table 14. ASTM D1037 Accelerated Aging Treatment

Step	Condition	Time
Immersion in water	49 +/-2°C	1 h
Steam and water vapor	93 +/-3°C	3 h
Freezing	-12 +/-3°C	20 h
Heating	99 +/-2°C	3 h
Steam and water vapor	93 +/-3°C	3 h
Heating in dry air	99 +/-2°C	18 h
Repeated for a total of 6 cycles. Total: 48 * 6 = 288 h		
Condition to equilibrium	20 +/-3°C and 65 +/-2% RH	Min. 48 h

Mild Weathering

The previously described treatments with acids are based on the assumption that long-term natural exposure under mild conditions is equivalent to short-term exposure under harsh conditions. Saad *et al.* (2016) exposed four groups of commercial panel products, oriented strand board, particleboard, fiberboard, and plywood, to 80 cycles of wet and dry cycles. Conditions during the wet phase were 40 °C and 90% RH for 120 hours and 40 °C without RH control during the dry phase for 48 hours. The total time for 80 cycles was 13,550 hours, which is approximately 1.5 years. Compared to the accelerated aging treatment defined by ASTM D1037 (2012), temperatures are consistently lower, with heating or freezing steps completely omitted. As shown in Table 14, the total time for the ASTM six-cycle is 288 hours. The mild treatment applied by Saad *et al.* (2016) caused irreversible thickness swell for all composites except plywood. A significant reduction in mechanical properties was observed during early cycles; however, the rate of reduction then leveled off. The same observations for the compression strength parallel to the fiber of solid pine sapwood, oak, and beech specimens were reported by Matejak *et al.* (1983). An exponential loss of compressive strength was measured for all species.

It can be assumed that the weathering effects of a mild treatment are limited by the resistance and durability of the substrate and the adhesive of the composite. The conditions of the ASTM six-cycle treatment are significantly harsher and much more likely to affect the substrate, adhesive, and bonding. Some adhesives, such as phenol-formaldehyde (PF) and methylene diphenyl diisocyanate (MDI), are highly resistant to moisture, and therefore damage to the integrity of the panel is limited.

Air Pollution

The deterioration rates of wood and wood-based composites by air pollution are rarely studied, mostly because damage and deterioration inducing processes are mainly dominated by moisture and radiation. In a study by Deppe and Schmidt (1991), a standard accelerated weathering treatment of wood-based composites was combined with either an acid bath at a pH of 2 or an acid-mix spray. Acids used were sulfuric-, hydrochloric-, and nitric acid. After 72 hours of exposure, the pH of the specimens was between 2.1 and 2.3. They were then exposed to various regimes of UV and water spray. Tension test results were compared to those of specimens naturally aged over nine years. All specimens had been initially coated and results showed that acid treatments can be used to accelerate weathering processes of coatings and adhesives related to air pollution and the excrements of microorganisms.

Parallel Studies

Natural vs. artificial weathering

In general, the literature cited in Tables 11 to 13 supports an assertion that accelerated weathering protocols involving both UV light irradiation and periods of water wetting affect wood's appearance and surface microstructure in ways similar to natural aging. Remarkably, this broad agreement does not appear to be highly dependent on the details of accelerated aging conditions, which can differ from study to study; however, for some properties, it is limited in time. Table 15 lists different publications that have examined the relationship of natural and accelerated weathering for different properties of solid wood and wood composites.

Grüll *et al.* (2014) investigated the integrity of different wood coatings under accelerated and natural weathering. Their study showed a logarithmic relationship between natural and artificial weathering. Initially, a short period of artificial weathering produced the same effects as a longer period of natural weathering. Throughout the exposure, the effects of artificial weathering become weaker and the progression of deterioration slowed down.

Many studies have examined the short- and long-term effects of natural and artificial weathering on the color of wood. UV radiation and moisture-induced color changes are typically quantified by the CIELab color space (Reinprecht 2018a,b). The effects of artificial and natural weathering processes depend on numerous factors, which makes it very difficult to compare different studies and draw general conclusions about the effects of natural and artificial aging processes.

Methods

To determine common trends among multiple aging studies, the results of 53 CIELab color space measurements were extracted from 18 publications. Each trend was composed of the type of weathering, an initial CIELab measurement, the results after short-term exposure, and a final measurement defined as long-term exposure. The length of short-term exposure varied, with an average of 2804 (+/-1836) hours for natural weathering and an average of 104 (+/-120) hours for artificial weathering. Long-term exposure was at an average of 15127 (+/-10171) hours for natural weathering and 1577 (+/-762) for accelerated weathering. The changes of each parameter of the CIELab color space were calculated for artificial and natural weathering for short-term and long-term exposure following Eqs. 2 and 3, where $\Delta_i short$ and $\Delta_i long$ are the short- and long-term changes of each parameter, and i_{short}, i_{long}, and $i_{initial}$ are the color space values before treatment and after short- and long-term exposure.

Short-term change of CIELab parameter

$$\Delta_i short = i_{short} - i_{initial} \tag{2}$$

Long-term change of CIELab parameter

$$\Delta_i long = i_{long} - i_{short} \tag{3}$$

The results are shown in Figs. 9A to C. Average lightness, L^*, initially decreases for both types of exposure; however, lightness again increases under artificial weathering after long-term exposure only. Out of a total of 28 natural weathering exposures, four datasets for short-term, and four datasets for long-term exposure do not follow this trend.

On average, lightness decreased by 7.5 and 3.8 after short-term natural and artificial weathering, respectively. Kržišnik *et al*. (2018) exposed four different wood-species to natural weathering for several years. The short-term measurements were taken after 2200 hours of exposure. Norway spruce, larch, and beech continued to decrease in lightness; however, oak showed an increase. The same observations were made by Liu *et al*. (2017) after short-term exposure of teak (*Tectona grandis* L.F.) and Mabberley (*Stereospermum colais*) under natural weathering.

Out of 23 datasets for artificial weathering, five showed an increase of lightness after short-term exposure. Increases were small for most of these observations and in the range of 1 to 6 (Kishino and Nakano 2004; Panek and Reinprecht 2016).

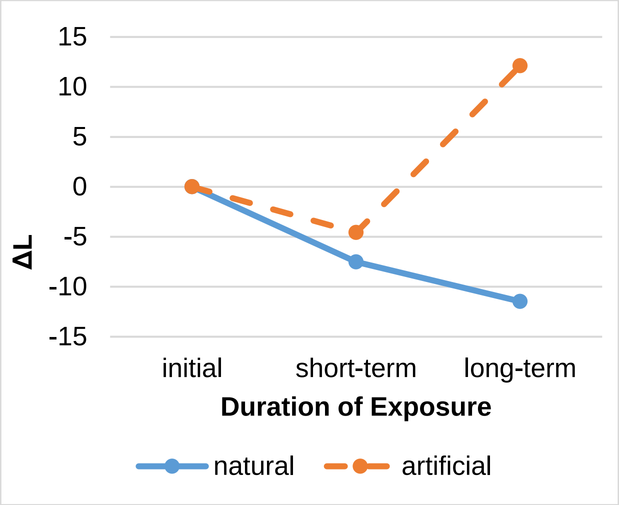


Fig. 9A. Average change of *L** after Short and Long-term Exposure. The sources of data for natural weathering in this figure and the next two are given in Table A (see Appendix). The data for artificial (accelerated) weathering came from the following sources: Huang *et al.* 2012a; Kishino and Nakano 2004b; Nzokou and Kamdem 2006; Panek and Reinprecht 2016; Silva *et al.* 2007; Xing *et al.* 2015.

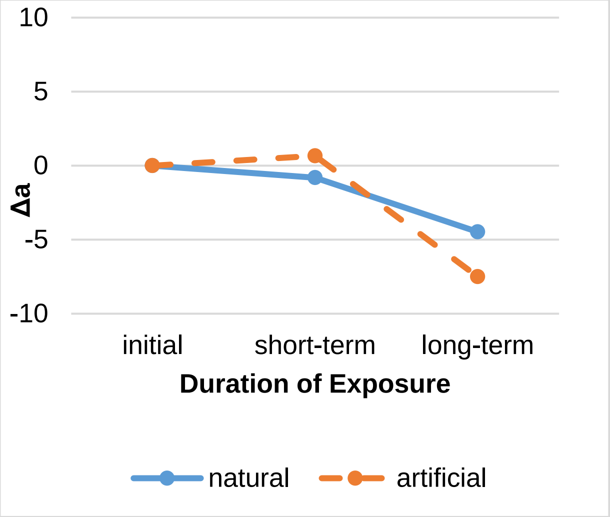


Fig. 9B. Average change of *a** after short and long-term exposure

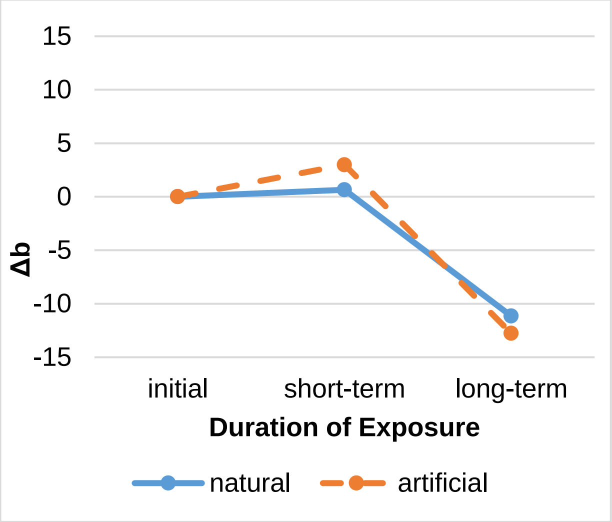


Fig. 9C. Average change of *b** after short and long-term exposure

The diverging trends of lightness for the two types of exposure after long periods are consistent for the majority of datasets. Jirous-Rajkovic (2004a) reported a subsequent increase of lightness for oak and fir after long-term exposure on a roof, facing south, after six months. The overall impact of the natural weathering regime on the lightness of both, oak and fir specimens, was reported to be small. Panek *et al.* (2016b) reported an initial decrease after short-term exposure and a subsequent increase of lightness after long-term exposure of untreated specimens of bangkirai (*Shorea obtusa* Wall., Sh. Spp.), massaranduba (*Manilkara bidentata* A. Chev.; M. spp.), and jatoba (*Hymenaea courbaril* L.) for 36 months. Their study assessed the effects of transparent and pigmented oils on color after natural and artificial weathering. Lightness initially drops for all three wood species. However, the drop was not as sharp for kusia (*Nauclea diderrichii* Merrill), a fourth tropical wood species included in the study. The authors point out that kusia has the lowest density compared to other species in their study and that a high surface porosity promotes the setting of dust particles. The lightness of the other wood species remained more stable after an initial drop of lightness.

For *a** and *b**, shown in Figs. 9B and 9C, the graphs for artificial and natural weathering follow similar trends. After short-term natural weathering, *a** decreased by 0.48 on average and increased by 0.84 after artificial exposure. On average, *b** increased by 0.64 after short-term natural weathering and 2.98 after artificial weathering. These trends are shown in Figs. 9B and 9C, where wood exposed to artificial weathering tends to show an increase in red (*a**) and yellow (*b**) color after short-term exposure. After long-term treatments, *a** decreased by 4.52 under natural conditions and 7.43 for artificial. The losses in *b** after natural and artificial weathering were very similar at 11.15 and 12.77 for long-term exposure. Under natural weathering, wood tends to immediately gain in green and blue color tones, with the former more pronounced. After long-term exposure, both exposure regimes cause the specimens to decrease in a and turn green. This trend is consistent for all datasets, without any exception. Changes in the blue and yellow color space, indicated by *b**, are not consistent after short-term exposure. After long-term exposure, all references report a decrease of *b** except for Kishino and Nakano (2004b). Their study reported an increase of *b** for *Eucalyptus robusta* after long-term exposure to artificial weathering. Though the plots in Figs. 9A through 9C represent the average effects based on a large number of studies, they don't show the wide diversity among the tests results. That diversity becomes apparent when one views the full data, obtained in several different laboratory conditions and with a wide assortment of wood species.

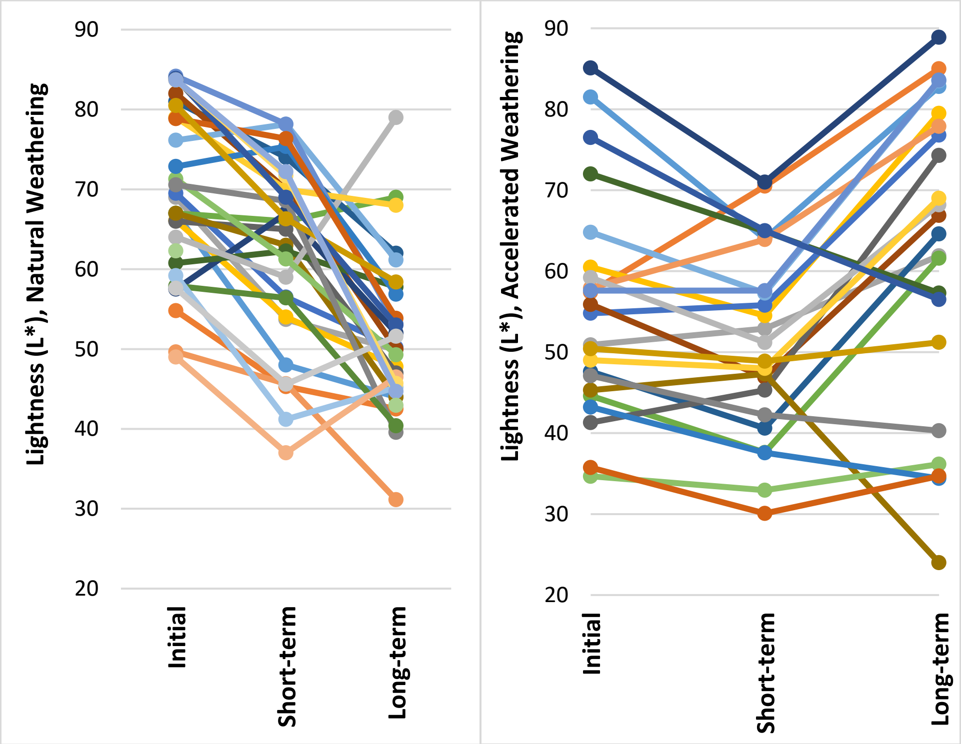


Fig. 10A. Effects of weathering on wood's *L** value

To give insight into the wide diversity of reported changes in color during both natural and accelerated weathering, Figs. 10A, 10B, and 10C show reported *L**, *a**, and *b** information, respectively, as reported in several studies involving weathering.

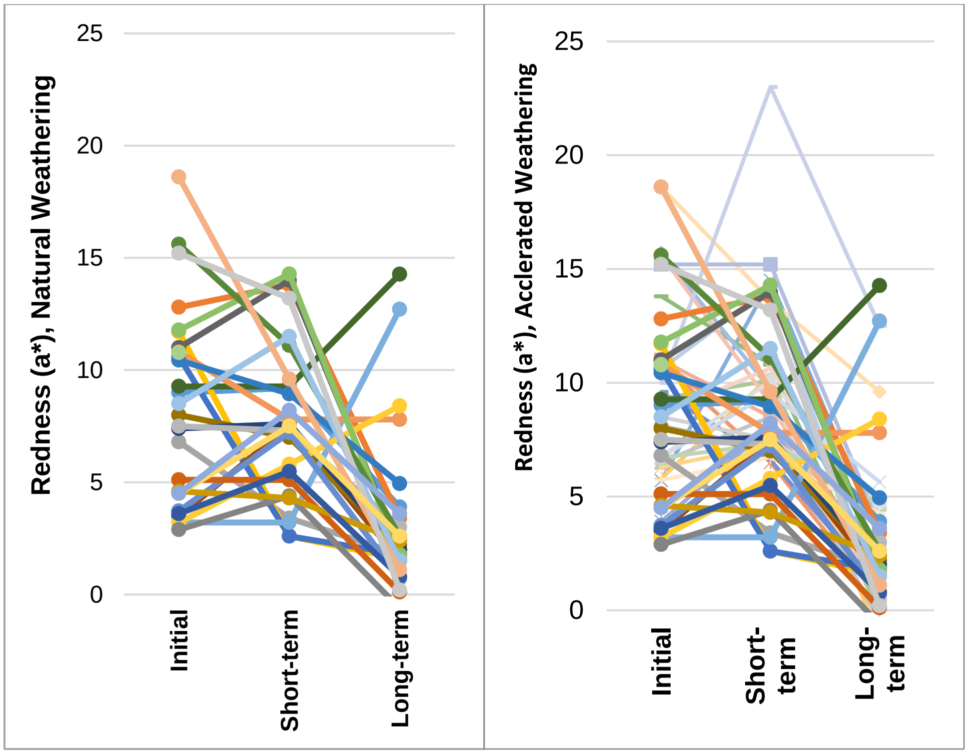


Fig. 10B. Effects of weathering on wood's *a** value

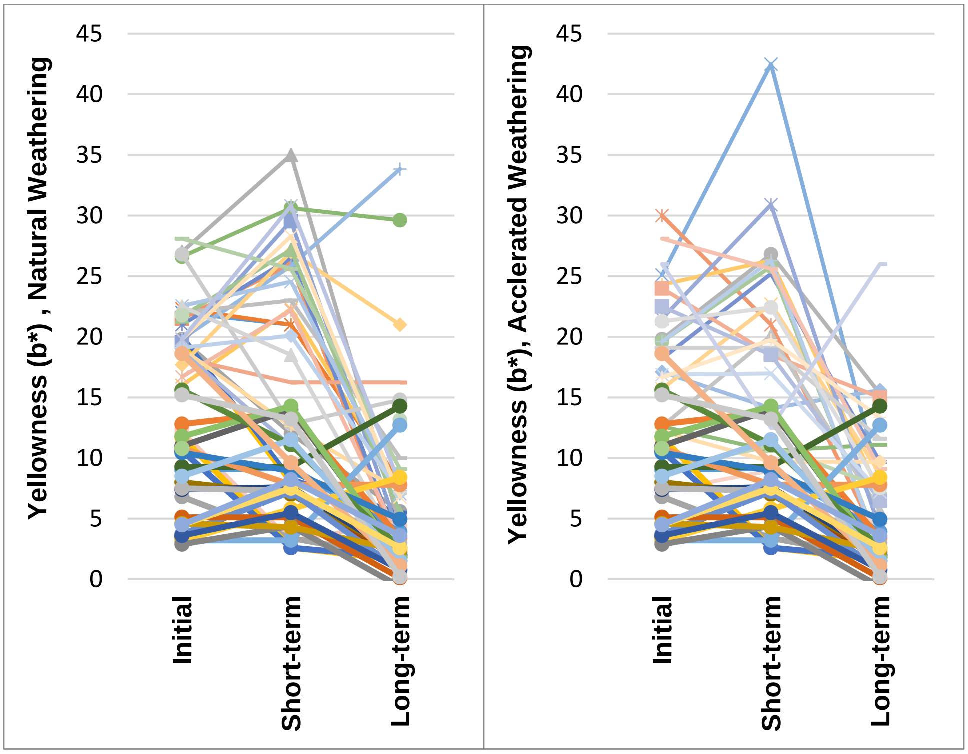


Fig. 10C. Effects of weathering on wood's *b** value

As noted earlier, Table A, which is in the Appendix to this document, provides a full listing of the data, together with literature citations.

Data points corresponding to natural weathering are shown at the left in each figure, whereas data corresponding to accelerated weathering are shown at the right. For each attribute of color (L^*, a^*, and b^*), the left-most data point corresponds to the initial color (not weathered), the middle point (pending the availability of data) indicates the color shortly after weathering begins, and the right-most point indicates the color after long-term weathering. By inspecting the shapes of the plotted lines in Fig. 10, one can observe that there are strong general trends but also exceptions to those trends. For instance, short-term natural weathering in many cases increased the lightness of the wood, but usually not, when considering many types of wood and detailed conditions of exposure. Long-term natural weathering generally decreased the lightness strongly, but there were three reports showing the opposite trend. Accelerated aging conditions were much more likely to show long-term increases in lightness, but there were three exceptions to the rule.

Table 15. Parallel Studies

Material	NW	Property	AW/NW Relationship (R^2 if available)	Source
SW	Vienna Austria (QUV)	Coating integrity	Logarithmic, (0.78)	Grüll *et al.* 2014
HW	Blacksburg, VA	Surface changes, chemical analysis	Cell wall changes after 30 days of AW and 500 h NW	Hon & Feist 1986
HW	NW sunlight through glass	CIELab, chemical analysis	Linear relationship below 60 h of AW (0.97 and 0.93), AW is 30 times faster.	Liu *et al.* 2019
HW	Horyuji temple, Nara, Senjuji temple, Mie, Japan	CIELab	Linear relationship between heat treatment and natural aging (r>0.99) in all color parameters. Color change after 921 years NW is equivalent to 6.7 h at 180 °C.	Matsuo *et al.* 2011
HW, SW	Trondheim, Norway, ATLAS	CIELab	None of AW recreated the exact effects of NW, but some relationship.	Ruther & Jelle 2013
HW	Zvolen, Slovakia, Xenotest	CIELab	Same macroscopic, microscopic, and chemical changes	Reinprecht *et al.* 2018a
HW	Fontainebleau, France	Glass transition of coating	75 h of AW reproduces similar variations of TG as 800 h of NW; acceleration factor 10.	Podgorski *et al.* 1996
SW/HW	Brazil	Mechanical properties	12-h of AW is equal to 6.22 days of NW.	Almeida *et al.* 2019a
Wood composites	Shizuoka City, Japan	IB	2-y outdoor exposure is equal to one cycle VPSD; 5-y outdoor is equal to 5 VPSD cycles.	Kojima and Suzuki 2011a
Wood composite	Berlin, Germany	Dimensional changes	12 weeks Xenotest is equal to 3-y NW.	Deppe & Schmidt 1979
Wood composites	Madison, WI	BS, IB	Linear relationship between MOR of outdoor and boil-dry and ASTM D 1037 AW (R=0.98)	Okkonen & River 1996
Wood composite	Shizuoka City, Japan	BS	Linear relationship between 5-y outdoor and 6 cycles JIS-B (0.82), APA (0.93), ASTM (0.93), VPSD (0.95) and 3-cycles of V313 (0.93)	Kojima and Suzuki 2011b
Wood composites	Madison, WI	BS, IB	MOR after 1, 5 or 20 BD cycles is suitable to predict MOR and MOE after 1, 5 and 10 years of NW.	River 1994
Wood composites		BS, IB	No Acid: 24 weeks AW and 4 – 6y of NW IB (0.89); BS (0.84) Acid: IB particleboard (0.96), IB Mineral Fiberboard (0.79)	Schmidt & Deppe 1996
SW: Softwood; HW: Hardwood; NW: Natural Weathering; AW: Artificial Weathering, BS: Bending Strength; IB: Internal Bond; MOR: Modulus of Rupture				

Mathematical relationships

Different observations about the mathematical relationship between artificial weathering, natural weathering, and various properties have been published. Table 15 lists different mathematical relationships that have been established between artificial and natural weathering, as well as underlying physical properties and conditions.

Solid wood

Hon and Feist (1986) conducted a study that compared changes to the surface of red oak (*Quercus* spp. *Erythrobalanus*), white oak (*Quercus* spp. *Leucobalanus*), yellow-poplar (*Liriodendron tulipifera* L.), and sweetgum (*Liquidambar styraciflua* L.). For all of the specimens, microscopic structural changes to the cell wall were found after 30 days of natural weathering and 500 hours of artificial exposure, which corresponds to an acceleration factor of 1.44. Reinprecht *et al*. (2018b) found that the potential for macroscopic defects, such as cracks, increases with prolongation of exposure. Natural weathering had a greater impact than artificial weathering; however, temperature differences during natural exposure could have impacted the outcomes of their study.

Good agreement between artificial and natural weathering was found in studies about color stability. Multiple examples exist that document a linear relationship between the types of exposure and the CIELab color space of wood. Liu *et al*. (2019) compared the effects of natural sunlight and artificial xenon light and identified a linear relationship up to 60 hours and 70-day exposures. Their aging processes were reported to accelerate aging by a factor of 30. Ruther *et al.* (2013) compared the impact on the color space of two accelerated weathering devices, ATLAS and a Rotating Climate Chamber (RCC), and natural weathering exposure. An accelerated low-temperature treatment at 22 °C in the ATLAS chamber was found to have an acceleration factor of 9. The RCC had a factor of 5 at a temperature of 63 °C. Correlation to natural weathering was strongest for these two treatments overall. Three other ATLAS exposure regimes with longer duration, and different combination of parameters within the same project did not show any correlation with the natural weathering results at all. Additionally, the recreation of color changes through accelerated weathering for Scots pine and Kebony Furu was found to be weak. In a study published in 2011, Matsuo *et al.* assessed the color changes under heat treatments and compared them to wood from historic structures. A 6.7 h treatment at 180 °C was found to have a linear relationship with the color after 921 years of natural weathering of wood extracted from a historic, old temple. Reinprecht *et al.* (2018a) point out that color changes are dependent on wood species and the conditions of aging. Therefore, any generalizations are to be taken with a grain of salt.

Wood-based composites

For commodities, such as plywood, particleboard, and oriented strand board, the replication of natural aging can be challenging for industrial applications. However, as previously mentioned, the intention of accelerated aging treatments of wood-based panels, such as the ASTM D1037 (2012) 6-cycle, is to quality control existing products and benchmark the performance of new or modified products. Durability, the retention of structural integrity over a specific duration, is well defined in product standards. By comparing the test results to existing products, that are known to perform well, conclusions about long-term performance can be drawn. Similar standards are the Japanese JIS-B (2003), the Engineered Wood Association's APA D-1 (1994), the European Standard Method V313 (2002), and the vacuum pressure soaking and drying method, VPSD.

Several studies have attempted to establish a correlation among different standardized aging treatments and between artificial and natural weathering. Aging of wood-based panels focuses on alternating, varying effects of temperature and moisture (Deppe and Schmidt 1979). Continual, periodic swelling and shrinking induce stresses that alter the integrity of the panel. However, too slow or too quick cycling does not correlate to the effects of natural weathering (Deppe and Schmidt 1979). The cited authors, therefore, considered the Xenotest device to better replicate natural exposure under accelerated conditions. The exposure schedule was based on the long-term effects of natural weathering. For un-coated panels, using a phenol-formaldehyde adhesive (PF), 12 weeks of Xenotest exposure were found to replicate 3 years of outdoor weathering. In a related study, Schmidt and Deppe (1996) replicated the effects of acidic rain and microorganisms. An acid mix, equivalent to the chemical composition of acidic rain and a pH of 2, was sprayed onto specimens during accelerated weathering. The pH was reduced from 4 to 2 to increase acidity by a factor of 100. The coefficient of determination between natural and artificial weathering and the internal bond was increased from 0.79 to 0.96 by introducing the acid spray. Back and Sandström (1982) point out that the type of artificial exposure should be based on the intended application. They provide the example of a gypsum board that will perform poorly in all boiling-based tests, but at room temperature will perform very well.

The ASTM D1037 (2012) 6-cycle is commonly used to assess the performance of wood-based panels in North America. Okkonen and River (1996) identified a linear relationship for the modulus of rupture (MOR) between natural weathering and the ASTM D1037 (2012) 6-cycle. Based on a study by Kojima and Suzuki (2011b), six cycles of this ASTM treatment were found to equal a 5-year outdoor period with a determination coefficient of R^2=0.93. The same number of cycles for the APA-cycle (1994), VPSD, and JIS-B (2003) yielded determination coefficients of 0.93, 0.95, and 0.82. The V313 method only needed 3 cycles for the same effects with a reported R^2 of 0.93. One, five, and twenty boil and dry cycles (BD), applied by River (1994), were found to equal 1, 5, and 10 years of natural weathering for bending strength and internal bond.

The retention of the mechanical properties of wood-based composites depends on the type of adhesive. Methylene diphenyl diisocyanate (MDI) and phenol-formaldehyde (PF) are known to exhibit the highest retention of structural integrity during cycling moisture exposure. In their 2011 study, Kojima and Suzuki (2011a) found that MDI-bonded panels had higher retentions than PF-bonded panels. This was found for MDF and PB. Urea- and melamine-formaldehyde adhesives are less resistant to moisture-induced deterioration and degrade faster (Deppe and Schmidt 1979). It has to be noted that wood-based panels are distinguished and classified by their intended use and that many types are not designated for outdoor exposure.

SIMULATED WEATHERING

Overview of Simulated Weathering

The focus of this section is on studies, demonstrations, and strategies to achieve effects in the wood that change its appearance and that may hold promise for increasing its sales value for a group of potential customers. In general, activities related to simulated weathering have not been directed towards gaining information related to what happens in the natural world. However, one of the goals of this section will be to look for scientific literature that can help explain some of the effects that have been achieved by the use of simulated weathering treatments.

The perception of what is an aged look of wood turns out to be very actively discussed in social media and ranges between the genuine aged and weathered occurrence to a somewhat rustic style, which does not necessarily have an aged or weathered appearance in scientific terms. The aged appearance might be indicated by unevenly degraded protective coatings on the wood surface, such as varnishes or paints. Color changes relative to the original color of new wood, such as darkening, yellowing, graying, or bleaching, are perceived as an indicator of aging. Grained surface texture as known from degradation by weathering, rough surfaces from sawing, worm action, and nail holes, as well as deposits on the wood surface such as concrete, can be considered as aesthetically appealing when it comes to interior design with "aged wood." To obtain a "natural finish" with an aged look, a variety of different techniques and materials are used, such as rough sawn surfaces, oil-based stains, bleaching oil, bleaching stains, or gray pigments (Feist 1992).

Simulated Weathering Treatments Involving Iron

Perhaps because iron is low in cost, generally eco-friendly, and easy to work with, systems involving iron in some way are among the most frequently presented on social media. As noted by Uzunovic *et al.* (2008), iron stains can be regarded as a common way to impart color to wood. Yeniocak *et al.* (2015) reported the staining of wood with a mixture of iron(II) sulfate ($FeSO_4$) and vinegar. The ferrous sulfate was found to be superior to various other metals considered.

When carrying out a search of scientific research involving iron and the weathering of wood, something surprising was found. Iron compounds can be used as a way to protect wood from weathering. For instance, Jirous-Rajkovic *et al.* (2004b) considered the use of ferric nitrate as a photostabilizer for stains at the wood surface. However, such treatment did not have any useful effect. Schauwecker *et al.* (2014) used wood surface treatment with iron oxide particles of different size and crystal shape as a strategy to minimize the effects of weathering. It was found that large dosages of iron oxide particles were needed to achieve meaningful reductions in the effects of weathering and that relatively large iron oxide particles tended to be more effective. Confirmatory results were reported by Sivrikaya and Can (2016).

Some forms of iron may promote the weathering of wood. Tribulova *et al.* (2019) observed that the presence of ferric sulfate, or its related products after exposure to the wood and air, promoted loss of cellulose when specimens of silver fir were subjected to accelerated aging (80 °C and 65% relative humidity for 30 days). Considering the acidic nature of iron(III) sulfate ($Fe_2(SO_4)_3$), such an effect might be attributed to the acidity, as mentioned earlier (Williams 2005).

Iron-tannate stain

The knowledge of ferric-tannates as colorants for wood, as well as the utilization of iron-gall-inks, purple-black or brown-black inks made from iron salts and tannic acid from vegetable sources (Mitchell 1923), goes back for centuries. Around the 7th century, iron-gall ink was introduced to central Europe by either Moors or Jews (Krekel 1999). Initially, the iron stain for wood was produced by soaking rusty nails and metal parts in vinegar. Iron stains are considered as chemical stains, since the wood is not dyed, but the metal salt is reacting with the tannins contained in the wood (Flexner 2010). Consequently, the tannin content of the wood affects the outcome of the staining process (Gardner 1939; Feist 1992). Other stains based on metal salts, including potassium dichromate, potassium permanganate, or copper sulfate, were utilized in the past. However, such metal salt-based stains were displaced by pigmented stains or dyes over time, since they are not always easy to control in the staining processes, and the materials themselves can be hazardous to health (Flexner 2010). Kelly (1912) and Gardner (1939) described recipes and applications for different chemical stains that are reacting with the tannins of wood. In modern approaches of artificial aging of wood, the ancient method of iron acetate and others has been experiencing a renaissance. Feist (1992) describes the mixture of iron stain with ferric chloride, along with other approaches for simulated aging of wood. Likewise, presented in tutorials available on YouTube, a growing number of woodworking companies appear to utilize iron-stains in combination with other methods in their self-developed processes, because of the similarity of the outcome to naturally aged wood. Naturally aged wood shows a great variety in the color spectrum, which is not easy to accomplish with monochrome stains. Since the tannin content of the wood varies, the results of staining with iron acetate shows a wide color spectrum.

Occurrence and complex formation

The polyphenol tannic acid (TA) present in plants is known to have antimutagenic, anticarcinogenic, and antioxidant activities (Lopes *et al.* 1999). It was found that TA is capable of reducing iron(III) through the formation of a TA-iron(III)-complex and decay due to electron transfer to form iron(II) (Bolobajev *et al.* 2016; Lau *et al.* 1989). TA can chelate iron ions, which leads to the formation of a stable iron(II)-tannate complex (Lopes *et al.* 1999). Stain formation on wood in contact with ferric iron is a well-known effect that is described to appear mainly in the extractive-rich heartwood (Krause 1954; Hon and Minemura 2000) on wood species that are rich in tannin content such as, *e.g.*, oak, cedar, walnut, redwood, and cherry (Williams 1999). In most of the reported cases, however, the iron stain is considered as a defect that reduces the value of the product and accounts for about 70% of the discoloration problems in the wood industry (Hon and Minemura 2000). Iron stains may occur in dry kilns due to contact with rusty metal or water from rusty steam spray pipes (Wengert 1997). Occasionally, contact with metal parts such as chains, forks, or surfaces might lead to stain formation when handling the wood in industrial processes (Wengert 1997). Fasteners, including nails and screws, can lead to stain formation in the inside of the wood surrounding the volume where the fastener penetrates the material (Uzunovic *et al.* 2008; Krause 1954). Iron exposed to the wood in the long-term in the presence of moisture also can catalyze moisture induced degradation (Williams 1999; Krause 1954). Krause (1954) anticipates a reduction of the natural decay resistance of the wood in the presence of iron. The author refers to a decrease in fungal toxicity of the hot water extractives in the presence of iron-containing material in an experiment with Swietenia heartwood. An effect on the water-absorbing properties of the stained wood as a potential effect for higher decay rates could not be assessed. Iron stain also was observed in standing trees. Goodell *et al.* (2007) reported discolored rings in the sapwood of dead Douglas-fir trees in the path of a volcano mudflow. Infiltration of the wood by iron was shown by chemical analysis. Uzunovic *et al.* (2008) described a similar effect for Western hemlock, which is capable of absorbing metals. The staining effect, however, does not occur until the metals migrate to the surface of the cut wood, where they are reacting on exposure to drying conditions. The penetration depth of the iron stain due to contact of wood with iron-containing items is reported as more than 0.4 mm (Wengert 1997) up to a few mm (Uzunovic *et al.* 2008). The penetration depth is dependent on the size of the iron particle, which determines the quantity of iron ions that can be leached into the surrounding wood substrate over time.

Influencing factors

The formation of iron stain is dependent on the concentrations of tannins and iron. Oak, a tannin-rich wood, can be stained with 0.0001% of iron in solution (Sandermann and Lüthgens 1953). Wood species with high levels of tannin content experience a significant decline in lightness due to iron stains (Hon and Minemura 2000). Hem (1960) investigated the formation of iron-tannate complexes in relation to the pH-value and concentration of tannic acid. According to the author, dissolved ferric iron is reduced to the ferrous state at a pH of less than 4 in a solution with a TA concentration of 5 to 50 ppm. At a pH of 4 or more, a material, black in color, containing iron ions and tannic acid is precipitated. With a TA concentration of 500 ppm at a pH of 5 or higher, iron-tannate complexes are formed. Un-complexed ferrous iron is oxidized and precipitated within a few hours. However, since the oxidation process takes place at a slow rate, some ferrous iron remains in the solution even after a month of storage. Iglesias *et al.* (2001) and (Feist 1992) have described the iron tannate complexes as being sparingly soluble and amorphous. The authors observed a change in the formation of the complex, in solution, over a reaction time of 6 months. In an early stage, the product consisted of a mono-type complex, whereas in a later stage of the reaction, mono- and bis-type complexes were formed. Likewise, Jaén and Navarro (2009) detected mono- and bis-type iron-tannate complexes formed by ferric iron with hydrolyzable as well as condensed tannins. Hon and Minemura (2000) concluded that woods with low pH values generally stain easily. The staining reaction was found to be at a maximum at a pH of 4 and a minimum at a pH of 7. However, for tropical wood species, this trend could not be recognized so clearly.

Iron stain formation was found to be dependent on the moisture content of the wood and relative humidity of the atmosphere. The fiber saturation point was described as a lower limit for the appearance of discoloration (Kollmann *et al.* 1951). To cause iron stains on dried lumber in interior applications, a high relative humidity of 95 to 100% must be reached in order to generate an equilibrium MC in the wood between 22 and 35% at room temperature (Hon and Minemura 2000). The formation of iron stain is accelerated in the presence of oxygen as well as high temperatures of 85 to 95 °C. The light did not seem to affect the stain reaction (Hon and Minemura 2000).

Applications on wood

Applications of iron tannate complexes in combination with wood are numerous. Kielmann (2018) blended phenol-formaldehyde resin (PF) with iron tannin-complexes (ferric chloride and ferric sulfate mixed with tannic acid) to modify and stabilize the color and improve the weathering performance of bonded beech wood. The mixture of ferric sulfate with tannic acid caused the highest color stability and the darkest color. However, the overall weathering performance in terms of minimum capillary water uptake in the course of weathering was reached by using unmodified PF. Evans and Schmalzl (1989) investigated the improvement of the weathering stability of radiata pine veneers by application of chromium trioxide and ferric chloride. While the modification with chromium trioxide improved the weather stability, ferric chloride caused a decrease in strength and an increase in weight losses during 35 days of natural weathering. This finding disagrees with the photoprotective effect of ferric chloride on wood reported by Hon and

Feist (1982). Evans *et al.* (1992) investigated the chemical changes of weathered wood specimens treated with chromium trioxide and ferric chloride with FTIR. The results led to the tentative conclusion that both treatments form photostable lignin complexes. However, chromium trioxide turned out to perform significantly better than ferric chloride.

Iron-tannin complexes have been shown to impart a brownish coloration to wood (Uzunovic *et al.* 2008; Yalcin *et al.* 2017; Kielmann *et al.* 2018). The cited authors used a mixture of ferric chloride, ferric sulfate, and hydrolysable tannin to stain wood. Hundhausen *et al.* (2020) investigated the graying effect of iron (II) sulfate on nine different wooden substrates under indoor and outdoor exposure for 51 weeks. The authors reported a graying effect on untreated wood species at a slow rate without the need for precipitation nor the presence of initial wood extractives under indoor conditions. Under outdoor conditions, the specimens decreased strongly in lightness during the first two months of exposure. UV-radiation was determined as the most critical factor in the graying process of the wooden surfaces in the presence of iron (II) sulfate. Early work by Salazar (1923, 1924) used a "tanno-ferric, tanno-acetic" method to stain wood. The reagent employed appears to have been ammonium iron(III) sulfate. This was used as a histological stain. The iron-based histological dying techniques of wood with iron-gall dye and iron-logwood dye was investigated by Canevari *et al.* (2016). The authors concluded that the logwood dye reached a greater penetration depth compared to the gall-dye. For both dyes, an intense alteration of the anatomical structure was found in the 300 µm subsurface area of the wood specimen. The alteration was attributed to an alkaline pretreatment of the wooden surfaces with NaOH. Baar *et al.* (2016) reported that tannin-rich types of wood could be discolored when in the presence of iron and moisture. Rolf *et al.* (1980) reported a very dark color of some boards that had been soaked in water at the lowest position of a ship's hold, where they had remained immersed in rusty water during shipping. The effect was attributed to the presence of iron tannate in the soaked wood. The iron presumably came from corrosion products in the water, and the tannin is a component of many wood types. Tomas *et al.* (1993) noted that tannins from tea were able to reduce iron species from iron(III) to iron(II). Goodell *et al.* (2006) likewise showed that phenolic compounds present in wood are able to reduce iron.

Iron-based nanoparticles also have been used to darken wood (Machova *et al.* 2019). The cited authors treated the wood with ammonia after the treatment with citrate-stabilized Fe_3O_4 nanoparticles. Because iron can form various hydroxides and oxides involving two different states of oxidation, iron(II) and iron(III), it is uncertain in most of these cited cases what was the final mineral form of the deposited material. More research would be needed to determine how the types of iron compound remaining in wood after such treatment may be affected by changes in moisture content either during wood drying after surface treatment or due to exposure to weathering.

Stability of iron stain

The iron-tannin stain can be removed by application of oxalic acid without affecting the original wood color (Koch 2008; Williams 1999; Hon and Minemura 2000). Iron tannate complexes are broken down by oxalic acid into a colorless ferrous salt (Uzunovic *et al.* 2008). Phosphorous acid, phosphoric acid, and hypophosphorous acid have also been reported to be effective in iron-stain removal. Sulfuric acid and hydrochloric acid exhibited a lower decoloring ability compared to oxalic acid (Hon and Minemura 2000). The iron tannin stain is characterized by a limited lightfastness (Flexner 2010; Kelly 1912).

Acid Treatments

Strong acids can cause discoloration on exposed wooden surfaces. Compared to iron stains, acid stains do not occur very often in woodworking processes. Acid hardeners for paints, coatings, and glues such as, *e.g.*, paratoluenesulfonic acid or hydrochloric acid can lead to reddish discoloration when used on wood surfaces or in wood composites with excess. Oxalic acid as well is reported to cause a red discoloration when applied to certain wood types in high concentration (Hon and Feist 1982).

Influencing factors

At pH-values between 2 and 5, oxalic acid and hydrochloric acid cause only weak, barely visible stains. At a pH-value of 1.5 however, strong red-brown or red stains occur (Hon and Minemura 2000). UV light was reported to accelerate the discoloration caused by acid. Takenami (1965), as reported in Hon and Minemura (2000), treated wood with a solution of oxalic acid at a pH of 1. Under the exposure of a mercury lamp, the wood obtained a maximum discoloration after 5 min. With indoor exposure, 5 days passed to achieve the same extend of discoloration, while storage in a dark place only caused a slight color change. The formation of the acid stain was independent of the presence of oxygen. The stain occurred in an atmosphere of nitrogen to the same extent as in an atmosphere with oxygen. Wood specimens extracted with acidic hot water did not show discoloration due to the acid treatment with oxalic acid (Hon and Minemura 2000). This finding leads to the tentative conclusion that the staining can be attributed to extractives.

Stability of discoloration

Acid stains can be removed by neutralization with an alkali such as sodium bicarbonate or calcium carbonate. Bleaching agents such as sodium chloride, hydrogen peroxide, or sodium hypochlorite break down the acid stain and remove the discoloration (Hon and Minemura 2000).

Acid treatments have been used by some researchers as a way to speed up tests of the breakdown of wood exposed to weather or related conditions. As noted earlier, in another context, Williams (1988) observed a strong acceleration in the weathering of wood that had been treated with sulfurous acid, which can be regarded as analogous to acid sulfite pulping. Williams (2005) attributed the effects of an increased rate of acid hydrolysis of the carbohydrates (cellulose and hemicellulose) in the wood. Schmidt and Deppe (1996) showed that spraying of an acidic mixture onto wood-based panels in accelerated weathering tests, resulted in a satisfactory differentiation of the strength behavior for different glue systems. Better agreement with outdoor tests was achieved.

Bleaching

Wood often becomes lighter in color as a consequence of long-term weathering (Feist 1982); therefore, it makes sense to consider bleaching procedures as a means to simulate some of the effects of weathering. In fact, one of the earliest scientific articles pertaining to the effects of outdoor exposure of wood was concerned with effects of ozone (Lyon and Fron 1929), which is known to be a bleaching agent for wood pulp.

In support of the strategy to use bleaching agents to treat wood, Herstedt and Herstedt (2017) showed that treatment of five types of rather dark wood with either oxidative or reductive bleach solutions was able to achieve substantially lighter shades. Work by Ozcifci *et al.* (2009) showed that the color of spruce and oak woods could be made lighter by treatment with hydrogen peroxide, ammonia, and their mixture. In addition, the bleaching treatments increased the surface roughness of the wood, which also is a commonly reported consequence of natural weathering (Forest Products Laboratory 1966; Kudela and Ihracky 2014; Tomak *et al.* 2014; Kerber *et al.* 2016; Oberhofnerová *et al.* 2017; Saad *et al.* 2017). Work by Mononen *et al.* (2005a,b) likewise showed that peroxide bleaching of silver birch wood can be used to lighten its color and roughen its surface.

A likely mechanistic connection between oxidative bleaching, using hydrogen peroxide, and photobleaching was reported by Hon and Feist (1992). It was shown that photooxidation of the wood surface gave rise to hydroperoxide species, which were detectable by diffuse reflectance infrared spectrometry. The hydroperoxide, after its formation, was involved in oxidative reactions leading to increases in carbonyl groups.

However, Budakci and Karamanoglu (2014) employed bleaching as a strategy to accomplish the opposite goal – to return the color of naturally weathered wood closer to its initial condition. Four bleaching solutions were compared. All of the bleached specimens became less hard, less glossy, and generally gray in color. The most favorable results were achieved with a mixture of hydrogen peroxide bleach and sodium silicate, which removed dark coloration from heat-aged specimens of chestnut, pine, oak, and beech.

Bleaching may also affect the results of subsequent photobleaching. This was shown in a study of stone groundwood pulp and corresponding thin specimens of *Abies* wood (Castellan *et al.* 1994). These researchers evaluated the effects of reductive bleaching with sodium borohydride on the color properties following photochemical bleaching. For both the groundwood and for the thin specimens, photobleaching eliminated the short-wavelength fluorescence of the material. The authors concluded that 4-hydroxy-3-methoxycinnamyl alcohol residues were being degraded by the light.

By means of chemical oxidation, which is analogous to many common bleaching treatments, Evans *et al.* (1992) showed that treatment of wood with sodium chromate tended to protect wood from some effects of natural weathering. The authors proposed that photostable lignin complexes had been formed. Follow-up work by the same authors (Evans *et al.* 1994) showed that treatment with chromate, a strong oxidizing agent, reduced micro-checking and degradation of pit openings associated with natural weathering. By contrast, treatment with ferric salts increased surface degradation during the subsequent natural weathering.

Stains

Given the fact that wood's color tends to be strongly changed during natural weathering, one of the simplest approaches that might be considered for simulated aging would be just to add colorants, which could be described as either staining or painting the surface of wood. Much of the scientific literature pertaining to the staining of wood has focused on analytical staining, with the purpose of improving photomicrographic images, judging the chemical nature of different tissues, *etc.* (Srebotnik and Messner 1994; Hubbe *et al.* 2019). Much less academic research attention has been paid to the technology of staining wood to change its color and other attributes (Feist 1977). The treatment of wood to change its color with stains is a broad area that merits research attention in the coming years.

Ammonia Fuming

Ammonia is a weak base that is able to darken the wood substance throughout the whole thickness (Weigl *et al.* 2007). In a well-known process called ammonia fuming, wood is exposed to gaseous ammonia (Tinkler 1921). The intensity of the color reached by the treatment is dependent on the ammonia concentration in the atmosphere, the time of exposure, and the wood species (Miklečić *et al.* 2012). Weigl *et al.* (2012) compared the properties of thermally modified wood with ammonia-fumed wood. Both processes can alter the wood color at a similar intensity. While the thermal modification is known to change the mechanical properties of the wood significantly, the authors reported that most mechanical properties of ammonia-fumed wood did not change. However, a significant increase in the equilibrium moisture content (EMC) was reported. Likewise, Weigl *et al.* (2009) reported an increase in EMC due to ammonia fuming for nineteen tested wood species. Furthermore, the authors described an increase in anisotropy of the wood. For most of the investigated wood species, there was an increase in dimension stability in the radial direction but a decrease of dimensional stability in the tangential direction. The so-increased anisotropy, affecting the shrinkage and swelling of the wood substance, should be taken into consideration if ammonia-fumed wood is used for construction and furniture applications. A good UV-stability of the ammonia-treated wood was reported compared to untreated wood (Weigl *et al.* 2007). Referring to the toxicity and strong irritative odor of ammonia, Petric *et al.* (2004) investigated the fuming of cherry wood with the less toxic substance ethanolamine. Satisfying results in terms of color changes and color stability were reported. An intensive plasticization and softening of the wood substance with a treatment of liquid ammonia was reported by different authors (Hietala *et al.* 2011; Suleman 2015; Bariska and Schuerch 1977; Owen and Pawlak 1989; Pawlak and Pawlak 1997). Owen and Pawlak (1989) proposed a breakdown of the lignin matrix by the liquid ammonia treatment as a reason for the increased softness and flexibility of the treated wood. Shen and Zhang (2018) described a method of softening the wood substance with the softening agent ammonium hydroxide followed by an abrasive treatment with sandblasting to increase the depth of the surface texture.

Alkali Treatment

Contact of wood with strong alkali can lead to a brownish discoloration. Fresh concrete typically has a pH of 12.5 to 13, which is strongly alkaline (Behnood *et al.* 2016). Wooden parts such as planks of shuttering or flooring that get in contact with the concrete often develop a discoloration (Hon and Minemura 2000).

Influencing factors

Takenami (1969), as reported in Hon and Minemura (2000), investigated the influence of pH-value on the occurrence of the discoloration on wood species. Only a slight stain occurred below a pH-value of 11.4. At higher pH-values, however, a fast stain formation was reported. The stain color was found to be dependent on the pH-value. Japanese cedar treated at up to pH 12.5 developed a reddish-brown color, whereas the color turned blueish at a higher pH. Light did not show significant participation in the alkaline stain formation. However, the presence of oxygen showed an increased intensity of the discoloration, which led to the conclusion of oxidative polymerization as a reaction for the formation of the colored substance (Takenami 1969, as reported in Hon and Minemura 2000). Takenami describes the formation of the discoloration dependent on the concentration of the water-soluble phenolic components such as tannins. Tannin-rich species that showed an intense discoloration only showed slight color changes after alkaline extraction.

Stability of discoloration

The stains can be removed by hypochlorite solution, an alkaline bleaching agent. Other bleaching agents, including hydrogen peroxide or dilute acid, are known to degrade the stains as well (Hon and Minemura 2000).

Degradation of the wood substance by acids and bases

Staining or discoloration of wood caused by chemicals is a result of the degradation of wood polymers. Often the originally uncolored extractives are converted in an oxidative process to products having an intense color (Goldstein 1984). According to this source, the main reactions responsible for the degradation of the wood substance are oxidative and hydrolytic. Besides the discoloration, these effects cause depolymerization of the wood components cellulose, lignin, and hemicelluloses and lead to decomposition of the wood substance. Gaseous compounds involved in the natural degradation process are oxygen, ozone, and carbon dioxide. However, especially in industrialized regions, acids and bases caused by pollution such as sulfur dioxide (SO_2) and gaseous components such as chlorine (Cl_2), nitrogen dioxide (NO_2), ammonia (NH_3), and aerosols are contributing to the degradation process (Wazny 1993). Williams (1988; 2005) investigated the degradation of wood due to weathering in combination with acids. Acids with a pH of 2 to 3 were found to increase the erosion rate due to weathering. None of the tested acids showed an effect on the degradation at pH 3.5 and above. Sulfurous acid was reported as effective in terms of wood degradation. Unger *et al.* (2011) have pointed out the dependency of the wood species on the susceptibility of degradation due to acid and alkali. Hardwoods such as oak and beech were reported to be less resistant than softwoods, such as pine and fir. This effect of degradation by acids and bases can be used in simulated aging of wood to increase the surface roughness and give a deeply grained and worn surface character. As shown in the patent section, there are several approaches of chemical degradation combined with mechanical treatments to alter the surface texture of wood.

Mechanical Treatment

To obtain a surface texture similar to naturally aged and weathered wood, mechanical surface treatments for artificially aged wood are conducted by manufacturers. Treatments are carried out in the form of planing with notched knives, sandblasting, rough sawing, wire brushing, and other mechanical means (Feist 1992; Lemaster *et al.* 2005). Wood that has been recovered from previous uses, such as boards from an old barn, is likely to contain evidence of abrasion, scratching, drill-holes, and many other features that might be regarded as imperfections. But in the case of weathered wood, or wood that is intended to give the impression of being weathered, such imperfections might be used to add to the appeal.

Sandblasting is a potential tool that is available to many technologists. Lemaster *et al.* (2005) reported the use of sodium bicarbonate and plastic particles to impart mild sandblasting to wood. The plastic particles were found to be more effective. Williams (2005) describes and shows some examples of the distinctive appearance of wood specimens that had been subjected to windblown sand. Such treatment can give a pattern in which the more resistant parts of the wood, such as knots and dense areas, protrude outwards relative to less resistant parts of the wood.

Thermal Treatment

Heat treatment of wood is well known to darken its color (Esteves *et al.* 2008; Esteves and Pereira 2009). Though natural weathering initially darkens many species of light-colored wood, the long-term effect usually can be better described as a graying effect (Feist 1982). Regardless, of this fact, heat treatment of wood is relatively easy to carry out, it is not very expensive, and the technology and equipment are well developed. Given the fact that the effects of heat treatment often are quite different from those of weathering, interested readers are encouraged to study other sources, such as the following (Mitsui *et al.* 2001; Ayadi *et al.* 2003; Brischke *et al.* 2007; Tuong and Li 2010; Chen *et al.* 2012).

The aging process of wood, with respect to the change of physical and chemical properties as well as color changes, can be compared with a mild thermal treatment (Kránitz *et al*. 2016). However, except for a changed color, the wood does not appear as aged or weathered in terms of a distressed surface. A controlled superficial thermal degradation, however, leads to a distressed and grained surface with altered chemical properties as well as changes in the color of the wood.

Shou Sugi Ban / Yakisugi

When searching the social media for techniques of artificial aging of wood, topics of charring or burning of wood surfaces frequently appear. Dependent on the charring method, wood species, moisture content, and post-treatments, the wood surface can appear as covered in char, overcast with "alligator skin cracks," in a dark brown color with a strongly grained pronunciation of early- and latewood, or only lightly stained (Kilian 2014). Carbonization of wood surfaces is known as an ancient wood preservation technique for construction that dates back for at least 2000 years to roman culture (McDonald-Wharry 2017). In the Japanese traditional technique called "Shou Sugi Ban" or "Yakisugi," the surface of cedar boards is charred one-sided to improve the weather resistance (Kymäläinen *et al.* 2017; Ebner *et al.* 2019), the resistance against microorganisms (Kollmann 1951; McDonald-Wharry 2017), and improvement of the flammability (Špilák *et al.* 2018). The practice of the "Shou Sugi Ban" technique dates back to the 18th century (Kilian 2014), where it was prevalent, especially to preserve claddings of buildings (Ebner 2019). The utilization of the technique decreased drastically when modern, non-biodegradable building materials were introduced to Japanese construction, and the wood supply in Japan began to decline (Kilian 2014). Nowadays, with high sensitivity for low environmental impact, recyclability of materials, as well as eco-friendly preservation techniques, "Shou Sugi Ban" has experienced a renaissance in Japan and the western world. The charring technique is considered as a highly interesting treatment for wood used in contemporary outdoor and indoor spaces (Fortini 2017; Sørensen *et al.* 2017; Cumming 2019; Crerar 2018). Several manufacturers in Europe and the USA are producing charred wood because of its sense as an aesthetical looking surface (Kymäläinen *et al.* 2017).

Even if charring is an old technique to preserve wooden surfaces, it has been sparingly investigated scientifically, and the knowledge of the process is mainly based on experience and tradition (Kymäläinen *et al.* 2017). Some studies have been conducted in Europe to investigate the suitability of the "Shou Sugi Ban" technique for European wood species (Kymäläinen *et al.* 2017, 2018; Čermák *et al.* 2019; Ebner *et al.* 2019). Investigated wood species were beech (*Fagus sylvatica* L.), Norway spruce (*Picea abies* L.), and Scots pine (*Pinus sylvestris* L.). It was concluded that European species are suitable for the charring technique.

Traditionally, cedar was used for "Shou Sugi Ban" (McDonald-Wharry 2017). Three lumber planks are tied together using water-soaked cords, chains, or tension springs to form a chimney in a triangular shape. The bottom of the chimney is lit by a small fire. Using the physical effect of the chimney, the wooden planks on the inside are charred up to the top. The energy for combustion is provided by the wood itself (Ebner *et al.* 2019). Kilian (2014) describes the utilization of handheld propane torches to char the wood surface as a common method in manufacturing. The technique can be found in social media as well. Ebner *et al.* (2019) describe the procedure of gas-burning wood charring machines. Planed wooden planks are transported by conveyor rolls and exposed to a flame produced by a gas mixture. The intensity and thickness of the char layer can be adjusted by regulating the feed rate and gas supply. Ebner *et al.* (2019) pointing out that under the aspect of gas costs and environmental impact, the utilization of a gas flame for charring the wood surface should not be the first choice. A lot of gas is necessary to obtain a uniform and consistent carbon layer, since the charring process is slow. Furthermore, the authors describe the gas-burning method as limited in terms of char layer thickness. A thickness of a 5 mm char layer, as obtained with the traditional method, is hard to achieve. Kymäläinen *et al.* (2018) and Čermák *et al.* (2019) used a steel heating plate to char the surface of different wood species at controlled temperatures between 250 and 400 °C. Likewise, Kilian (2014) describes electric heating plates as a common method for charring.

Physical and chemical changes due to the charring process

Exposed to a high temperature, the physical and chemical properties of wood are changed (Hill 2006). Thermal decomposition of the wood polymers starts at a temperature of 105 °C (Ebner *et al.* 2019). The highest temperature for thermal modification is 250 °C, which marks the ignition point of wood. At 270 °C, the formation of a carbon layer starts, while at a temperature of around 300 °C to 360 °C, a direct flaming ignition occurs (Babrauskas 2002). The combustion with an open flame turns the wood surface black in an exothermal degradation process and slowly develops a carbon layer (Ebner *et al.* 2019).

The charred surface can improve the weathering performance of wood. The carbon layer reduces moisture uptake (Ebner *et al.* 2019). Čermák *et al.* (2019) found the EMC of charred beech was significantly reduced due to the decrease of hydroxyl groups, an increase of cellulose crystallinity, and an increase of lignin cross-linking. The char layer prevents air from entering internal parts of the cross-section (Ebner *et al.* 2019) and improves the flammability of wood (Špilák *et al.* 2018; Niemz 1993). The 3 to 5 mm thick charcoal layer is unattractive for microorganisms such as wood-decay fungi (Kollmann 1951), which accounted for an increased pH-value of the charred wood (Weber and Quicker 2018). UV-irradiation has no altering effect on the surface, since the wood components celluloses, hemicelluloses, and lignin are mostly degraded on the first outer millimeters of the wood (Kymäläinen *et al.* 2017).

Post-charring surface treatments are used to modify the appearance of the charred wood. Loose char particles can be removed with different brushes, manually, or with brushing machines. Especially for interior applications, protective oils and varnishes are applied to the surface (Kilian 2014). Traditionally an oil from the fruit of the khaki tree is used besides tung oil and flaxseed varnishes (Ebner *et al.* 2019).

Different charring techniques influence the uniformity, intensity, and thickness of the char layer. The resulting variations do have an impact on the physical and chemical properties of the treated wood surface, especially concerning the weathering resistance. Considering simulated aging of wood for decorative aspects, a high penetration depth of the charring treatment might not be necessary, since the protective effect might play a subordinate role. Further research must be conducted to investigate the color changes of charred wood surfaces dependent on wood species and charring technique and as well as the surface texture obtained by charring.

Patents Related to Artificial Aging or Weathering of Wood

When researching a topic such as artificial aging or weathering of wood, which has not attracted much attention from a scientific standpoint, it might be interesting to investigate alternative sources. Such sources might include gray literature, social media, and patents. In the patent arena, some inventors develop processes and knowledge based on trial and error rather than based on scientific knowledge or scientific methods. However, even if some of the developed methods by patent holders are not explained entirely in a scientific way and might not be applied in the industry yet, they can be seen as an inspiration for possible applications and future fields of research.

Several patents related to the topic of artificial aging of wood are aimed at achieving decorative effects. Xiang (2019) describes a method of moisturizing the wood surface of dried wood followed by a harsh three-step drying process to increase the crack formation and surface roughness. Likewise (Eugenievich 2014) applies a harsh drying process to the top layer lamellas of 3-layer parquet flooring planks. Several patent holders describe devices to emboss a relief into the wood surface for a grained appearance (Lin *et al.* 2018; Zhejiang 2006) as well as combinations of heat treatment and embossing techniques (Magnusson 2010). Shen and Zhang (2018) describe a method of softening the wood substance with the softening agent ammonium hydroxide followed by an abrasive treatment with sandblasting to increase the depth of the surface texture. Likewise Gmach (2015) applies chemicals in the form of different acids and bases in combination with a heat and radiation treatment and a subsequent mechanical process to degrade the wood substance on the surface. Different charring techniques are described with gas burners (Zhao 2007; Cottingham 1987) and with a radiant heat panel (Lee and Chaiken 1979). A mixture of metallic sodium or potassium and sand is used by Lee (1976) to char the wood surface. The mixture is distributed on the wood surface and activated by water vapor. In an exothermal reaction, the sodium or potassium melts and burns the surface. In a subsequent brushing step the residuals of the mixture and loose char particles are removed. Numerich (1977) defines a process to generate the so-called Lichtenberg Figures on the wood surface. A device that produces a high voltage current from about 6,000 to 25,000 volts is used to form charred lines between two electrodes on the wood surface. The lines resemble worm tracks or insect caves.

CONCLUDING COMMENTS

Wood is a natural material. But live trees do not typically expose their xylem tissues directly to the weather. Rather, live trees are typically covered by bark. In such a context, the natural weathering of wood – and the fact that wood can achieve a relatively stable, weather-resistant layer that can last for many years – might be regarded as a somewhat accidental occurrence, rather than presenting a clear evolutionary advantage to trees. Despite the fact that nature does not, by itself, divide the wood up into boards and hold them up facing the weather, the fact that humans build wooden structures, and sometimes these are unprotected by paint, has provided a rich laboratory within which to study the hidden potential of wood to take on the beauty of weathered wood, while revealing many fascinating aspects related to the biology, chemistry, and physical of natural materials.

The first area of focus of this review article dealt with natural weathering, including both its attributes and its mechanistic explanation. Though the published record is complicated, possibly reflective of the complex character of natural materials and weather, there appears to be a broad consensus regarding both the character and the causes of weathering of wood. Sequential and repeated exposure to both solar radiation, especially the UV component, with intermittent washing by rain, appear to be of central importance. The depth of degradation of wood appears to be related to the limited transmission of UV light through wood. Even when the UV-absorbing lignin component near to the surface has been degraded and washed away by rain, the loosened cellulosic fibers at the weathered wood surface are expected to have an enhanced ability to scatter light. Since light transmission through a material depends on both absorbance and scattering, wood maintains its ability to resist deep penetration of UV light even after long exposure. Though many published reports have shown that weathering can occur in the absence of any fungal colonization, published findings suggest that some form of bluestain colonization is the rule, rather than an exception when unprotected wood is exposed for a long time outdoors in moderate to moist climatic conditions. Bluestain typically makes weathered wood appear somewhat darker and bluer than it would otherwise have been.

The second area of focus was accelerated weathering, *i.e.*, laboratory methods to allow prediction of natural weathering, but in a much shorter length of time. Accelerated weathering tests no doubt have been helpful for technologists within the wood protection industry who have developed new varieties of clear-coats, paints, and treatments with oils, *etc.* Accelerated weathering tests, carried out with planned variations, also have helped to uncover and confirm aspects of the weathering mechanism. In particular, the central importance of rain events has been persuasively demonstrated by comparing the results of accelerated weathering tests with and without the application of water. Despite the widespread use of accelerated weathering tests, the literature contains little information that would allow a technologist to judge which conditions of accelerated aging are most likely to provide an accurate prediction of natural aging effects. Another inherent uncertainty is that even if there were a set of conditions that best allowed predictions to be made about unprotected wood surfaces, there is no guarantee that the same accelerated weathering conditions would provide a fair estimate of the relative effects of different coatings, each of which might have different levels of vulnerability towards the imposed conditions. For this reason, even with continuing progress in the development of accelerating weathering test methods, it will never be possible to abandon natural weathering tests as a final arbiter to understand the natural process.

Simulated weathering, the penultimate theme dealt with in this review, represents a burgeoning of entrepreneurial collection of often-informal efforts to reap some of the attractive attributes of weathered wood, but to achieve them by use of quick, practical alteration of ordinary wood. The posted videos on social media present a wide range of treatment variations, giving rise to a range of difference changes in wood’s appearance. Emphasis is often on the use of readily available ingredients and convenient processes. Whether or not the results resemble those of natural weathering, a recognizable change needs to be made to the wood’s appearance, and each such variation has the potential to attract willing customers.

The emergence of social media as an engine of the generation of new ways to treat wood represents a new twist. Wood, which long has been associated with tradition and stability, now is being made to appear weathered or worn out, but at the same time new and innovative. The sheer number of participants and viewers of YouTube videos having to do with simulated weathering of wood is large and possibly greater than the total number of people who have read one or more of the numerous scientific articles cited in this work. There can be debate about whether or not each of the YouTube videos contains information of interest to scientists. There appears to be little communication between the two audiences – the scientific community with its main attention focused on natural weathering, and the popular presentations focused mainly on quick, practical, potentially money-making treatments. Efforts are clearly needed to carry out scientific investigations to better understand some of the most promising of the simulated weathering treatments that have appeared on social media.

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APPENDIX

Table A. Compilation of Color Data for Natural Weathering and Accelerated Aging of Various Wood Species

Natural Weathering											
Wood type	Init.	Short	Long	Init.	Short	Long	Init.	Short	Long		Citation
	*L**	*L**	*L**	*a**	*a**	*a**	*b**	*b**	*b**		
Corymbia	67.0	48.0	44.0	9.0	9.2	3.9	22.0	21.0	8.0		Delucis *et al.* 2016
Eucalypt	54.8	45.3	42.5	12.8	13.8	3.4	22.3	21.0	8.0		Delucis *et al.* 2016
Gympie	69.0	53.7	49.9	6.8	3.4	1.8	19.8	12.0	5.6		Gonzalez-C *et al.* 2015
Blue gum	66.1	54.0	47.8	11.7	2.6	1.6	19.8	7.9	4.8		Gonzalez-C *et al.* 2015
Rose gum	69.5	56.5	50.2	10.6	2.6	1.8	20.1	8.3	5.5		Gonzalez-C *et al.* 2015
Oak	67.0	66.0	69.0								Jirous-Rajkovic *et al.* 2004
Fir	81.0	74.0	62.0								Jirous-Rajkovic *et al.* 2004
Norway spruce	82.0	70.0	50.0	3.5	7.5	1.5	21.5	26.0	2.0		Kržišnik *et al*. 2018
Larch (LD)	66.0	65.0	47.0	11.0	14.0	2.0	27.0	35.0	4.5		Kržišnik *et al.* 2018
Beech (FS)	67.0	63.0	44.0	8.0	7.0	2.2	16.0	22.3	7.5		Kržišnik *et al.* 2018
Oak (Q)	57.5	67.0	52.0	7.4	7.6	2.0	21.0	26.5	2.5		Kržišnik *et al.* 2018
Teak	60.8	62.3	57.8	10.1	9.3	14.3	26.6	30.6	29.6		Liu *et al.* 2017
Mabberley	76.2	78.2	61.2	3.2	3.2	12.7	19.8	25.8	33.8		Liu *et al.* 2017
Basralocus	49.7	45.7	31.2	10.8	7.8	7.8	18.2	16.2	16.2		Liu *et al.* 2017
Oak	64.0	59.0	79.0	7.5	7.3	3.0	22.0	23.0	10.0		Machova *et al.* 2019
Fir	79.0	70.0	68.0	3.2	5.8	8.4	17.7	27.0	21.0		Mohebby 2015
Spruce	84.2	78.2	53.2	3.7	7.2	0.7	19.5	29.5	3.5		Oberhofnerová 2017
Doug fir	71.3	61.3	49.3	11.8	14.3	1.8	21.7	27.2	5.5		Oberhofnerová 2017
Oak	72.9	75.4	56.9	10.4	8.9	4.9	22.6	24.6	7.1		Oberhofnerová 2017
Maple	78.9	76.4	53.9	5.1	5.1	0.1	16.7	22.2	3.2		Oberhofnerová 2017

Poplar	70.6	68.6	39.6	2.9	4.4	-0.6	26.8	12.8	14.8		Oberhofnerová 2017
Natural Weathering											
Wood type	Init.	Short	Long	Init.	Short	Long	Init.	Short	Long		Citation
	*L**	*L**	*L**	*a**	*a**	*a**	*b**	*b**	*b**		
Kusia	57.9	56.4	40.4	15.6	11.1	2.6	28.1	25.6	9.1		Panek & Reinprecht 2016
Bangkirai	59.2	41.2	45.2	8.5	11.5	1.5	19.1	20.1	7.1		Panek & Reinprecht 2016
Massaran	49.0	37.0	46.5	18.6	9.6	1.1	12.2	3.2	4.7		Panek & Reinprecht 2016
Jatopa	57.6	45.6	51.6	15.2	13.2	0.2	22.5	18.5	2.5		Panek & Reinprecht 2016
Spruce -R	83.7	71.7	45.7	4.5	7.5	2.6	19.8	28.3	6.8		Reinprecht & Panek 2015
Spruce -S	83.7	72.2	44.7	4.5	8.2	3.6	19.8	30.8	7.8		Reinprecht & Panek 2015
Beech	62.3		43.0	10.8		-1.5	21.8		13.2		Turkoglu *et al*. 2015
AVG:	**69.1**	**62.0**	**51.2**	**8.4**	**7.8**	**3.1**	**20.8**	**21.1**	**9.1**		
Accelerated Weathering											
Wood type	Init.	Short	Long	Init.	Short	Long	Init.	Short	Long		Citation
	*L**	*L**	*L**	*a**	*a**	*a**	*b**	*b**	*b**		
Jack pine	57.4	70.5	85.0	10.9	6.5	0.5	30.0	21.0	3.0		Huang *et al.* 2012
A acreana	50.9	52.9	61.9	8.1	7.1	1.6	19.8	26.8	15.3		Kishino & Nakano 2004b
A auriculiformis	60.5	54.5	79.5	5.8	10.3	-1.2	24.3	26.3	7.1		Kishino & Nakano 2004b
Diptercarp	54.8	55.8	76.8	9.6	6.6	1.1	18.2	25.2	9.7		Kishino & Nakano 2004b
E marginate	44.6	37.6	61.6	13.8	10.8	0.5	12.6	10.6	11.1		Kishino & Nakano 2004b
E robusta	47.6	40.6	64.6	15.7	9.7	0.6	17.1	14.1	15.6		Kishino & Nakano 2004b
Shorea	55.9	46.9	66.9	11.0	8.5	0.5	24.0	18.5	15.0		Kishino & Nakano 2004b
Tabebuia-hi sg	41.3	45.3	74.3	6.5	8.5	-0.5	12.6	20.1	5.6		Kishino & Nakano 2004b
Tabebuia-lo sg	45.3	47.3	24.0	6.3	7.3	1.3	15.7	22.7	8.7		Kishino & Nakano 2004b
Red pine	85.1	71.0	88.9	3.9	8.1	1.4	21.5	30.9	4.1		Nzokou & Kamdem 2006

Red oak	72.0	64.9	57.3	9.3	10.1	-0.1	19.6	25.8	2.5		Nzokou & Kamdem 2006
Bk. cherry	64.8	57.3	83.5	10.6	14.2	0.0	19.6	26.3	2.3		Nzokou & Kamdem 2006
Accelerated Weathering											
Wood type	Init.	Short	Long	Init.	Short	Long	Init.	Short	Long		Citation
	*L**	*L**	*L**	*a**	*a**	*a**	*b**	*b**	*b**		
Bangkirai	59.2	51.2	68.2	8.5	7.5	4.5	19.1	19.1	11.6		Panek & Reinprecht 2016
Massaran	49.0	48.0	69.0	18.6	13.6	9.6	12.2	9.7	9.7		Panek & Reinprecht 2016
Jatopa	57.6	57.6	83.6	15.2	15.2	3.7	22.5	18.5	6.5		Panek & Reinprecht 2016
Ipe roxo	34.7	33.0	36.2	6.7	7.3	4.7	9.2	11.0	7.7		Silva *et al.* 2007
Itauba	43.2	37.6	34.4	6.7	9.6	5.6	16.9	17.0	7.2		Silva *et al.* 2007
Macarand	35.7	30.1	34.7	8.6	10.6	3.4	7.3	9.0	4.5		Silva *et al.* 2007
Tatajuba	47.1	42.3	40.3	6.8	10.1	4.7	21.3	22.4	7.5		Silva *et al.* 2007
Tauari	50.4	48.9	51.2	5.7	6.7	4.3	16.7	19.8	13.4		Silva *et al.* 2007
Larch	76.5	65.0	56.5	10.0	23.0	12.5	26.0	12.5	26.0		Xing *et al.* 2015
AVG:	**55.4**	**51.6**	**63.4**	**9.6**	**10.2**	**2.7**	**19.1**	**20.7**	**9.2**		

Notes: “Init.” = Initial reported value given in the reported work; “Short” = either the value after the shortest reported time, or if available, the value corresponding to a maximum in the *a** value near to the initial time but not the initial observation; “Long” = the final reported data at the maximum exposure time of the cited work. Larch (LD) = *Larix decidua*; Beech (FS) = *Fagus sylvatica*; Spruce -R = rough, Spruce-S = smooth, Tabebuia-hi sg = relatively high specific gravity; Tabebuia-lo sg = relatively low specific gravity