coatings

Article

Effects of Climate on Exterior Wood Coating Performance: A Comparison of Three Industrial Coatings in a Warm-Summer Mediterranean and a Semi-Arid Climate in Oregon, USA

Kent Davis [1], Scott Leavengood [2,*] and Jeffrey J. Morrell [3]

[1] Cambium R&D, LLC, Albany, OR 97321, USA; kent.cambium@gmail.com
[2] Wood Science & Engineering, Oregon State University, Corvallis, OR 97331, USA
[3] Ecosciences Precinct, University of the Sunshine Coast, 41 Boggo Road, Dutton Park, QLD 4102, Australia; jmorrell@usc.edu.au
* Correspondence: Scott.Leavengood@oregonstate.edu; Tel.: +1-541-737-4212

Abstract: Wood exposed in exterior applications degrades and changes color due to weathering and fungal growth. Wood coatings can reduce the effects of weathering by reducing the damaging effects of ultraviolet light, reducing water absorption, and slowing fungal growth on the surface. Coating performance depends on the blend of resins, oils, and pigments and varies considerably among different wood species and conditions. Specific information describing expected service for different wood species and exposure conditions is not commonly available; certain combinations may work well in one climate or on one timber species, but underperform elsewhere. This study compared the performance of three industrial wood coatings on two wood species for two temperate climates under natural weathering conditions. Most of the coatings/species combinations lost their protective properties within 12 to 15 months; however, fungal growth was more prevalent at the wetter site than at the drier site for several combinations. Film-forming coatings often peeled and cracked, while penetrating coatings weathered and changed color relatively uniformly during the study. While no coating was completely effective, the results illustrate the benefits of using coatings that promote the development of natural, uniform-patinaed wood surfaces. The findings also guide coating maintenance programs for mass timber structures exposed to natural weathering conditions.

Keywords: wood coatings; exterior exposure; mass timber coatings; wood weathering; UV degradation

Citation: Davis, K.; Leavengood, S.; Morrell, J.J. Effects of Climate on Exterior Wood Coating Performance: A Comparison of Three Industrial Coatings in a Warm-Summer Mediterranean and a Semi-Arid Climate in Oregon, USA. *Coatings* **2022**, *12*, 85. https://doi.org/10.3390/coatings12010085

Academic Editor: Marko Petric

Received: 3 December 2021
Accepted: 6 January 2022
Published: 12 January 2022

1. Introduction

Wood used in exterior structural and appearance applications weathers in four ways, sometimes simultaneously [1,2]. It can lose color and turn silver or gray, mold fungi can disfigure the surface, decay can develop with prolonged wetting, and/or it can experience dimensional changes that lead to surface checking and warping. Weathering rarely causes structural issues; rather, most short-term weathering impacts the aesthetic attributes that likely influenced the initial specification of wood. Graying is caused by exposure to the ultraviolet (UV) component of sunlight, which preferentially degrades the lignin and extractives on the wood surface [2,3]. The often simultaneous presence of fungal growth on wood surfaces (commonly referred to as mold) causes unsightly discoloration characterized by black deposits. Discoloration caused by graying of the wood surface or the unarrested mold growth is often unsightly, requiring long-term expense to maintain the desirable visual attributes.

Exterior wood coatings are commonly applied to limit UV-caused degradation or reduce water absorption to minimize dimensional changes, and may also contain biocides that slow fungal growth. Coating performance is highly dependent on interactions between the coating formulation, wood chemistry, and the environment. While opaque coatings (i.e., paint) that block UV light generally perform best, they mask the beauty of the wood. As a result, transparent or semitransparent coatings are often used in appearance applications. These formulations contain combinations of oils, resins, binders, pigments, stains, biocides, stabilizers, and UV absorbers that either form a protective film on the surface or penetrate the wood to provide deeper protection of the wood fibers, lignin, and cellulose [1,2,4–6]. Most coatings protect wood surfaces for 8 to 18 months [2,7–11]; however, a few coatings perform for up to 24 months [10,12], depending on the wood species, the climate, and the coating type. Coating degradation typically begins with yellowing, loss of gloss, and embrittlement that leads to the development of checks or splits in the wood that allow moisture penetration and slow subsequent drying [2]. Coating damage also allows UV damage as well as fungal colonization of the wood beneath [2]. These processes often result in light-colored spots and streaks [2] or black and blotchy blemishes on the surface. Some varnishes will develop milky patches [13] or they may crack [13,14], and peel, providing increasing entryways for moisture and microorganisms that further decrease coating integrity.

Despite decades of research to improve coating performance, few coatings provide long-term protection without supplemental maintenance [15]. Unsightly surface appearance often requires refinishing the wood surface or leads to complete replacement. Time-consuming procedures, such as washing and sanding, are required to remove mold, algae, and degraded wood on heavily damaged surfaces before the application of a new coating. These procedures can increase building maintenance costs. Therefore, it is advantageous to initially apply a coating that prevents surface degradation associated with UV weathering color change and fungal attack.

Increased use of mass timber elements in mid- to high-rise construction projects has resulted in designs that intentionally expose timber to moisture and UV, increasing the risk of surface discoloration. Architects, designers, and builders require information about the performance of coatings that provide the best and longest protection to wood in exterior applications without obscuring the desirable visual attributes. Few coatings can maintain the bright original appearance of the wood without regular cleaning and reapplication and it may be more useful to protect the wood from fungal attack while allowing the surface to weather to a natural, uniform gray patina. Such aesthetics have been considered desirable with certain groups of end users [16,17].

Many older studies used visual assessments to quantify changes in coating appearance over time [2]. These ratings are subjective, but useful within the context of the same study with the same evaluator. Changes in surface color can also be expressed with changes in the components of the $L^*a^*b^*$ (also referred to as CIELAB) color space where L^* relates to lightness, and a^* and b^* are chromaticity coordinates [18]. An increase in a^* indicates increased saturation of red, while a decrease in a^* indicates increased saturation of green. An increase in b^* indicates increased saturation of yellow and decreases in b^* indicate increased saturation of blue [18]. This system helps minimize the subjectivity of the coating assessment.

Expected performance information is especially important in temperate climates such as those found in the Pacific Northwest (PNW) of North America. Although the overall climate is characterized by dry, warm summers and wet, cool winters [19], environmental conditions can vary considerably within relatively short distances across major north-south mountain ranges in the region, which may lead to dramatically different weathering outcomes for a given wood species used across a vast area with differing environmental conditions. Unfortunately, there are few comparative studies of the long-term performance of commercial coatings that can be used to help select the most appropriate coatings for a given wood species in a specific climate type.

The objective of this research was to expand on a previous study evaluating 12 coatings on 5 wood species exposed to 18 months of natural weathering in a warm-summer Mediterranean temperate (Koppen climate Csb) climate in Corvallis, OR, USA [11]. This paper extends some of that data and compares the performance of three of these coatings on Douglas fir heartwood or acetylated radiata pine sapwood exposed at the original site with color change performance at a higher elevation semi-arid temperate (Köppen climate classification BSk, i.e., a cold semi-arid climate) site in Madras, OR, USA. The sites differ markedly in precipitation, average monthly temperature, UV intensity, and humidity, leading to a hypothesis that these differences will help differentiate between coatings on the species studied. Additionally, the previous study focused on a novel clustering analysis to group the coatings by changes in the *L*a*b** parameters. Although related, this study focused on the comparison of coating performance in two dramatically different climates. This study used methods developed by Davis et al., [11], with a relatively inexpensive flatbed scanner and standard image analysis procedures to measure color change on 2 species treated with 3 coatings over 25 months of natural weathering in the semi-arid climate of central Oregon (Davis et al., [11]).

2. Methods

2.1. Coatings and Wood Species

The samples were prepared as previously described by Davis et al., [11]. Briefly, kiln-dried lumber was cut into clear, knot-free coupons 19 mm thick, 75 mm wide, and 150 mm long. The wood species used were Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) and commercially acetylated (hereafter referred to as acetylated wood) radiata pine (*Pinus radiata* D. Don. Accoya, Accsys, Arnhem, The Netherlands). Both species are commonly used for either facades and cladding or for structural applications in mass timber buildings exposed to natural weathering conditions within the greater PNW and beyond. The samples were representative of commercially available material and were primary flat-sawn, although the Douglas fir samples contained nearly equal proportions of flat and vertical grain. The density of the Douglas fir sample material was within the published ranges for the species [15]. The density of the acetylated wood was 0.508 g/cm^3. The samples were conditioned at 20 °C and 65% relative humidity (RH) before treatment. The coatings were applied to freshly sanded surfaces according to manufacturer instructions, including the recommended number of coats.

A total of 36 coupons were produced for each species and allocated into 6 treatment groups, each containing 6 samples for both studies [11]; however, a subset of wood species (presented above) and coatings was selected for comparison between the sites. The coatings (Table 1) selected represent three of the major coating types that are commercially available (i.e., film-forming, penetrating oil, and water-based). Old Masters Spar Urethane (OM) is a film-forming urethane with UV absorber [20], Heritage Natural Exterior Finish (HN) is a penetrating oil with UV absorber and mildewcide [21], and Sansin Coating System 1 (S1) is a multipart pigmented water-based penetrating coating with UV absorber [22]. The coatings were commercially available when the study was initiated; however, formulations may have changed since and the exact product may no longer be available. The coated samples were stored away from UV light until they were scanned using an Epson Perfection V200 flatbed scanner as high-resolution.tiff images (Epson America, Inc., Los Alamitos, CA, USA) at a resolution of 4800 dpi.

The three coatings showed moderate performance in terms of overall color change in 18 months on Douglas fir in Corvallis, but the overall color change was lowest for OM, moderate for S1, and highest for HN on acetylated wood in that location [11]. Therefore, as suggested above, we would expect varying levels of performance in terms of both overall color change and *L*a*b** parameters for the different coating/species in an environment with drier and colder conditions. Due to technical difficulties, four (of six) acetylated wood coupons were used for the OM and S1 coatings and three samples were used for the HN coating. Three Douglas fir coupons were used for the OM and HN coatings and four were used for the S1 coating. The first exposure period occurred between 20 November 2018 and 4 June 2019, the second period occurred between 15 August 2019 and 15 May 2020, and the third occurred between 1 June 2020 and 15 March 2021. The samples experienced a total of 25 months of natural exposure at the site. The long and irregular sampling periods were due to COVID-19 work and travel restrictions.

Table 1. Coatings used to evaluate the effects of the test site on the ability to protect against color change in Douglas fir and acetylated radiata pine in an aboveground field trial.

Manufacturer	Coating Code	Commercial Name
OLD MASTERS P.O. Box 286 Orange City, IA 51041, USA	OM	Old Masters Spar Urethane
Heritage Natural Finishes P.O. Box 97 Philomath, OR 97370, USA	HN	Heritage Natural Exterior Finish
The Sansin Corporation 111 MacNab Avenue Strathroy, ON N7G 4J6, Canada	S1	Multicoat: 1-P8475 2-P8476 3-P8476

2.2. Installation Location

Coupons were exposed to natural environmental conditions at Oregon State University's Peavy Arboretum, approximately 12 km north of Corvallis, OR, and at the University's Central Oregon Agriculture Research and Extension Center north of Madras, OR. Samples were placed randomly on racks so that one wide face (coated face) was exposed at a 45° angle oriented at a 180° (south) azimuth (Figure 1).

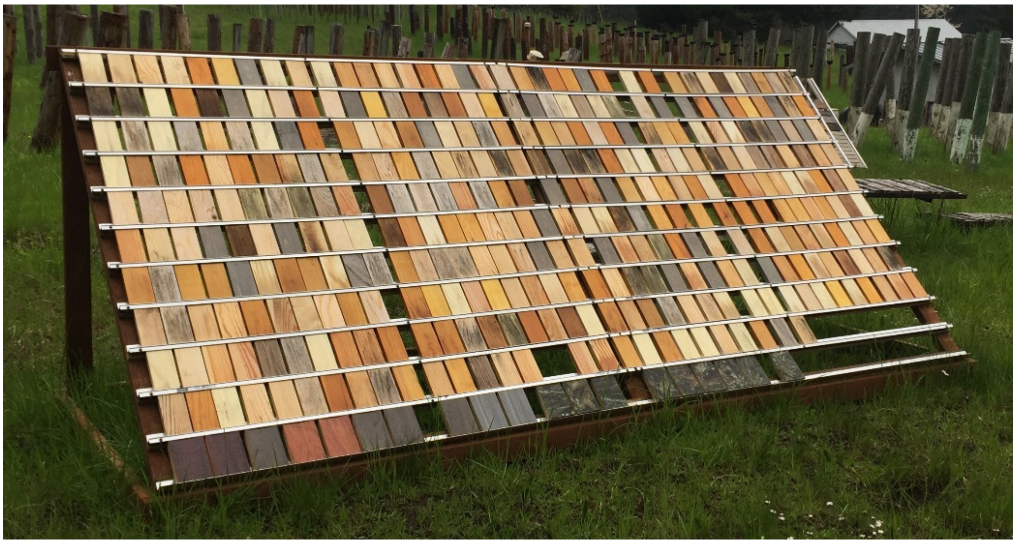

Figure 1. Coated samples exposed to natural weathering at a 45° angle on a test fence near Corvallis, OR. The same setup was used in both the Corvallis and Madras locations.

2.3. The Madras Site

The Madras site has a semi-arid temperate climate with short, warm, and dry summers, and very cold, snowy, and partly cloudy winters [23]. The site receives 332 mm of precipitation per year (including 259 mm of snow) that mostly falls in the winter and spring months between October and April when the average monthly temperatures range between 0.6 and 9.4 °C [23]. The site is located 680 m above sea level with average daily shortwave radiation ranging between 1.5 kWh/m^2/day in December to 7.9 kWh/m^2/day in July [23]. The average monthly maximum and minimum temperatures and monthly rainfall were obtained from the weather station located at the Research Center (Figure 2).

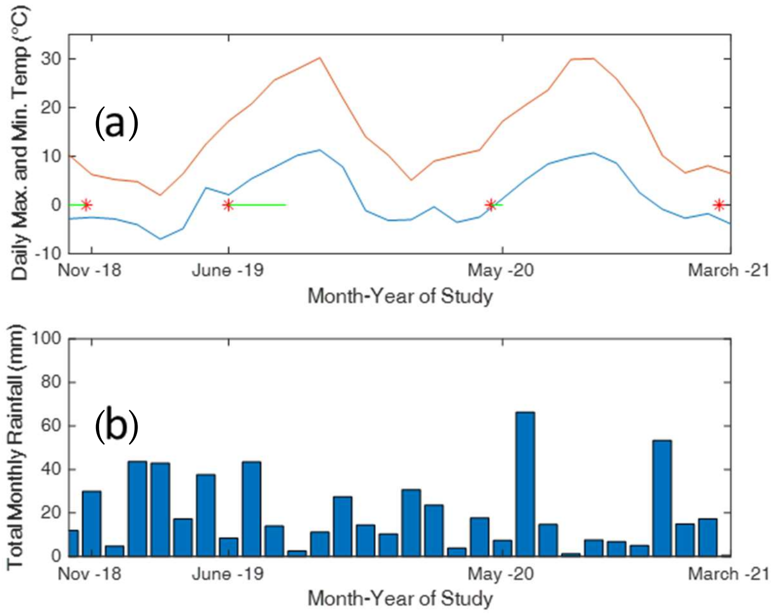

Figure 2. Maximum and minimum temperature and total monthly rainfall for the Central Oregon Agriculture Research and Extension Center during the study. Red stars indicate when samples were scanned, and green lines indicate when samples were in storage awaiting return to the site. (**a**) mean monthly daily maximum and minimum temperature, (**b**) total monthly rainfall for the site.

2.4. The Corvallis Site

The Corvallis site has a Mediterranean temperate climate with cool, wet winters and dry, warm summers. The average rainfall is around 1.2 m per year, mostly in the winter months between October and March when the average monthly temperatures range between 4 and 12 °C. The average monthly maximum and minimum temperature and the monthly rainfall (Figure 3) were obtained from the closest weather monitoring station at the Oregon State University Hyslop Farm, approximately 7 km southeast of where the samples were exposed. The direct normal solar annual radiation index at this site is approximately 3.5 kWh/m^2/day.

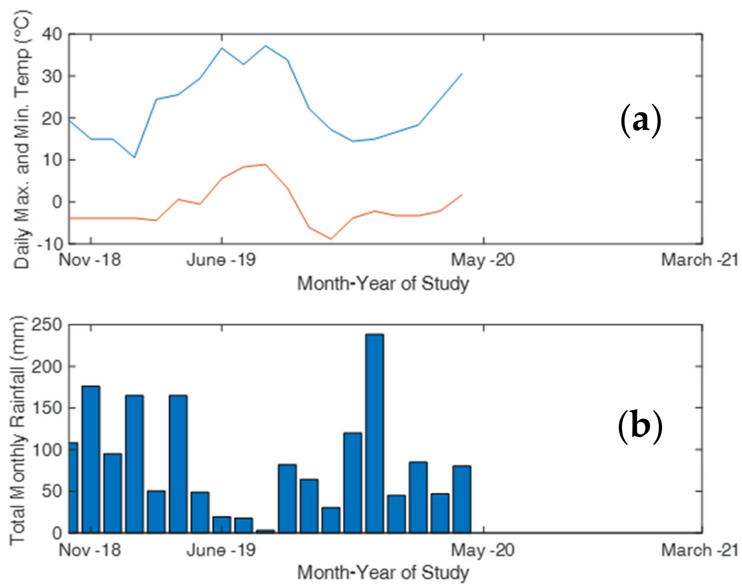

Figure 3. Maximum and minimum temperature and monthly rainfall for the Oregon State University Hyslop Farm during the study. (**a**) mean monthly daily maximum and minimum temperature, (**b**) total monthly rainfall for the site.

2.5. Analysis

The analysis closely followed the procedures described by Davis et al., [11]. Briefly, images were converted to $L^*a^*b^*$ format using MATLAB (Mathworks, Natick, MA, USA), cropped to minimize edge effects, and the mean values of L^*, a^*, and b^* were calculated for each image. The mean differences between the initial and the first, second, and third sampling interval were calculated for each image and the total color change (ΔE) was calculated as:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

Welch's ANOVA [24] functions in MATLAB (version R2021a) were used to determine significant differences between the mean ΔE of each species/coating pair for each exposure interval at $p < 0.05$. A Games–Howell [25] multiple pairwise post hoc comparison test in MATLAB was performed to determine significant differences in ΔE, L^*, a^*, and b^* for each coating within each species group. This test was also used to determine differences between mean values of the same variables from the former study [11] and the corresponding sampling intervals from this study.

3. Results

3.1. Color Change (ΔE)

There were few significant overall color change (mean ΔE) differences between the surfaces treated with the coatings within species used in this study for each interval (Table 2). Examples of significant differences include the color change for S1 at 6 months and 15 months for which the change was significantly lower for Douglas fir than for acetylated wood and an increase in ΔE for Douglas fir surfaces treated with OM or HN and exposed for 25 months. The color change was also significantly higher for surfaces treated with OM or HN after 25 months of exposure for Douglas fir than for acetylated wood. Overall, there were no significant differences in ΔE between any of the surfaces for either species or coating with an exposure period over the study (data not shown). Recall that ΔE does not measure the direction of color change, but rather the Euclidean distance between two locations within the $L^*a^*b^*$ color space. The lack of significant differences may be due to the large variation within sample groups and small sample size.

Table 2. The ability of different coatings to protect Douglas fir heartwood and acetylated radiata pine sapwood from UV damage as measured by ΔE for each species/coating combination over a 25-month exposure at two sites with differing climates. * indicates significant differences between each species/coating combination as determined by Welch's ANOVA.

	Mean ΔE					
Coating	**6 Months**		**15 Months**		**25 Months**	
	Douglas Fir	**Acetylated Wood**	**Douglas Fir**	**Acetylated Wood**	**Douglas Fir**	**Acetylated Wood**
OM	16.4	20.0	5.9	17.5	20.6 *	13.3
HN	12.6	20.7	16.2	23.5	26.7 *	9.1
S1	12.0 *	29.9	6.7 *	22.4	19.2	16.4

3.2. $L^*a^*b^*$ Color Parameters

As with Davis et al. [11], the data are presented separately by wood species, given the potential for performance to vary with wood species.

3.2.1. Douglas Fir

ΔE increased significantly during the first 6 months of exposure at both sites, decreased during the second 9 months, and increased during the last 10 months for Douglas fir surfaces treated with OM or S1 (Figure 4), while ΔE increased throughout the exposure for surfaces treated with HN (Figure 4). ΔL^* decreased very little during the first 15 months of the study; however, it significantly decreased over the remaining 10 months for coated samples (Figure 4). Little change in Δa^* was observed during the first 6 months; however, dramatic decreases were measured after 15 months of exposure for all three coatings (Figure 4). Unlike the trends observed for ΔL^* and Δa^*, Δb^* increased during the first 6 months for all coatings, returned to initial conditions for OM and S1 at 15 months, and decreased dramatically during the last 10 months of exposure (Figure 4).

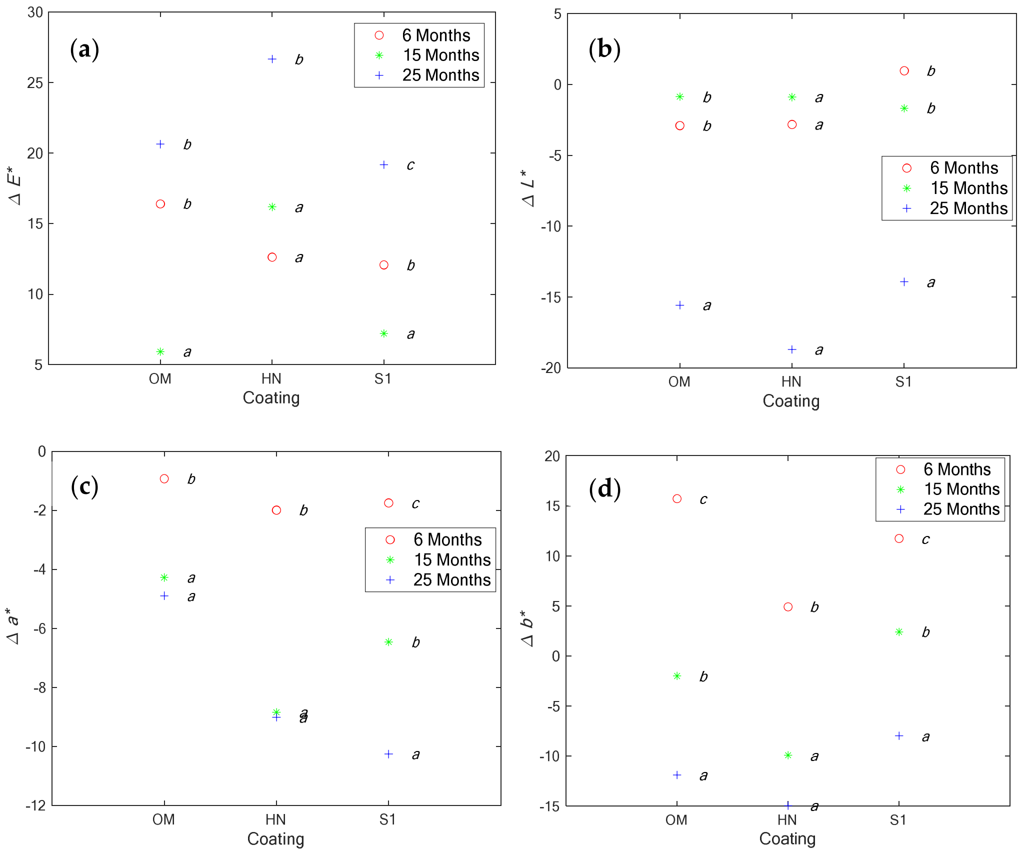

Figure 4. Games–Howell pairwise mean differences in ΔE, ΔL^*, Δa^*, and Δb^* for three coatings on Douglas fir samples exposed outdoors for 24 months. Superscripts with the same letter indicate that means between intervals do not differ significantly at $p < 0.05$. (**a**) color change (ΔE), (**b**) ΔL^*, (**c**) Δa^*, (**d**) Δb^*.

There were some significant differences in the changes in $L^*a^*b^*$ values of different species/coatings combinations between the Corvallis and Madras locations (Figure 5). ΔE, Δa^*, and Δb^* increased more for OM-treated Douglas fir exposed at Corvallis than at Madras for the first two intervals of the study, while ΔL^* decreased more at Corvallis than at Madras despite the longer exposure times in that location. Other notable differences occurred between surfaces treated with HN for Δa^* and ΔL^* and surfaces treated with S1 for ΔE, Δa^*, and Δb^* during the last interval of the study. Values between the locations were typically significantly lower at Corvallis than at Madras, indicating samples often darkened more in Corvallis than at Madras.

The trends in ΔL^*, Δa^*, and Δb^* are reflected by RGB images of samples throughout the study (Figures 6–8). In general, the samples dramatically darkened during the last interval but did not markedly change visually during the first and second interval of the study for samples at Madras, OR, USA. The darkening was likely the result of considerable decreases in ΔL^* and Δb^*, which caused increased blueness and darkness. The Corvallis samples tended to show minor darkening and discoloration for the second interval and major discoloration and surface degradation by the end of the study for surfaces treated with OM and HN. Visually, Douglas fir samples appeared to darken more in Corvallis after

18 months than did samples in Madras by 25 months. In addition, the OM and S1 coatings cracked and peeled more in Corvallis.

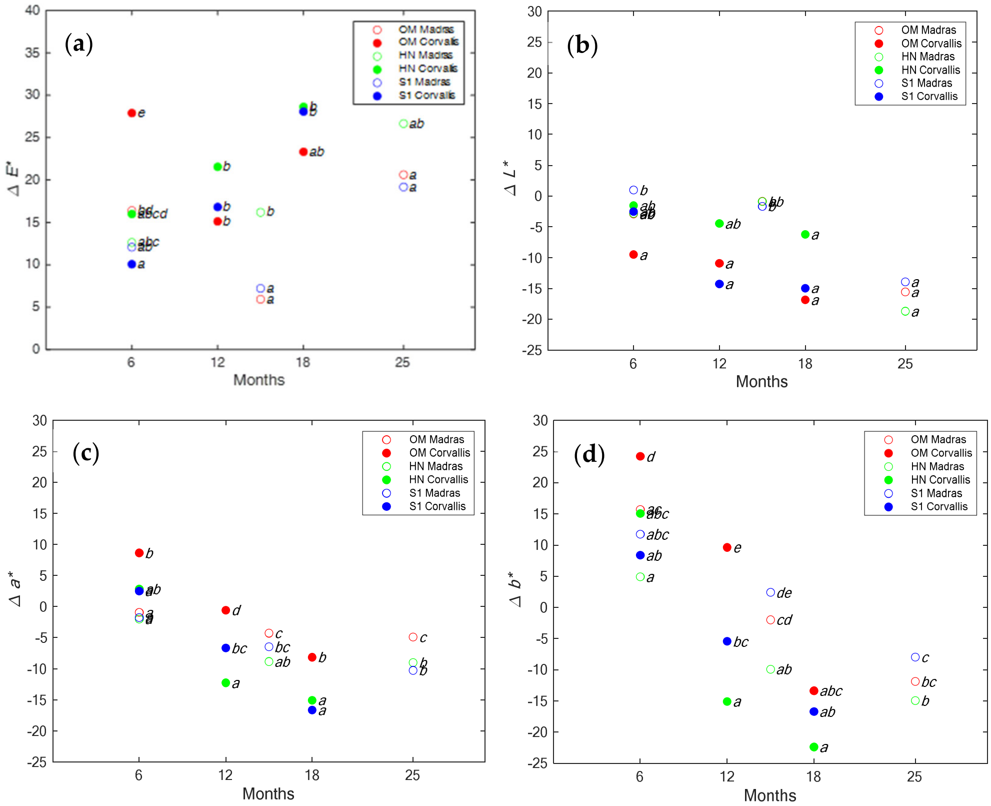

Figure 5. Games–Howell pairwise mean differences in Δ*E*, Δ*L**, Δ*a**, and Δ*b** for each species/coating combination from each location for Douglas fir. Values with the same letter indicate that means between intervals do not differ significantly at $p < 0.05$. (**a**) color change (Δ*E)*, (**b**) Δ*L**, (**c**) Δ*a**, (**d**) Δ*b**.

Figure 6. Examples of the same Douglas fir wood specimen treated with OM and exposed outdoors on a test fence near Corvallis, OR, for 0, 6, 12, and 18 months (**top row**) and a similarly treated specimen exposed in Madras, OR, for 0, 6, 15, and 25 months (**bottom row**).

Figure 7. Examples of the same Douglas fir wood specimen treated with HN and exposed outdoors on a test fence near Corvallis, OR, for 0, 6, 12, and 18 months (**top row**) and a similarly treated sample exposed at Madras, OR, for 0, 6, 15, and 25 months (**bottom row**).

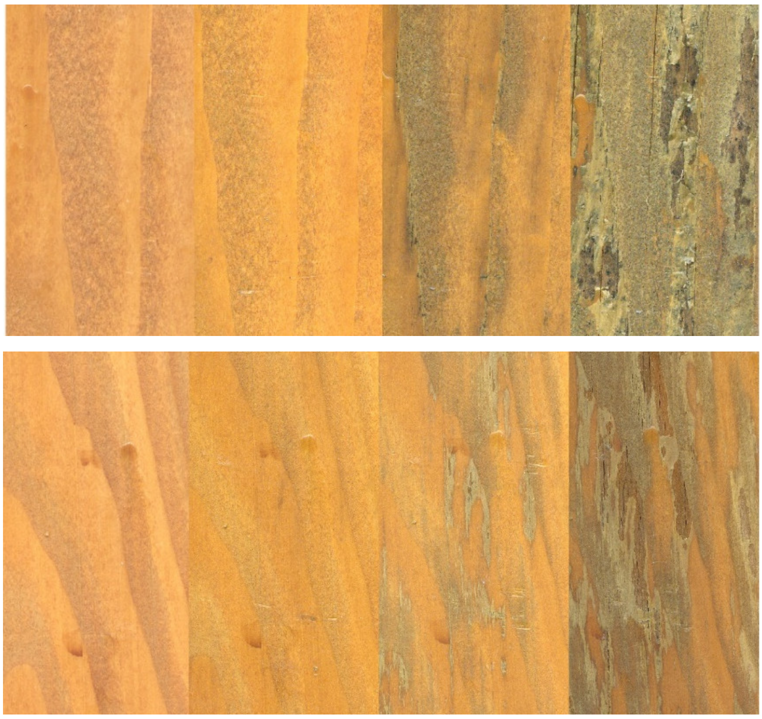

Figure 8. Examples of the same Douglas fir wood specimen treated with S1 and exposed outdoors on a test fence near Corvallis, OR, for 0, 6, 12, and 18 months (**top row**) and a similarly treated sample exposed at Madras, OR, for 0, 6, 15, and 25 months (**bottom row**).

3.2.2. Acetylated Wood

Color change patterns of acetylated wood differed from those for Douglas fir during the study. For example, Δ*E* increased dramatically during the first 6 months, only to decrease during the remaining intervals for surfaces coated with S1 (Figure 9), but did not change significantly for the other coatings. Δ*L** decreased significantly during the last interval for surfaces treated with S1 only, Δ*a** increased during the last interval for surfaces coated with OM only, and Δ*b** decreased during the last interval for surfaces coated with OM and HN only (Figure 9).

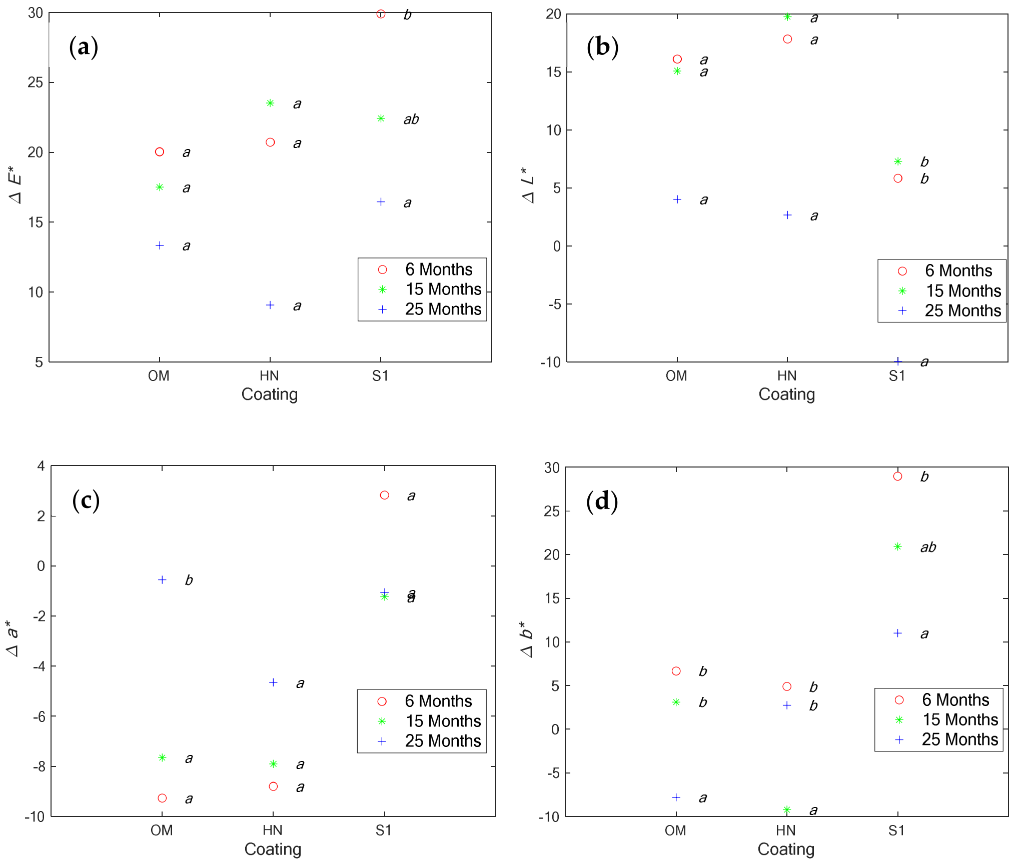

Figure 9. Games–Howell pairwise mean differences in Δ*E*, Δ*L**, Δ*a**, and Δ*b** for each coating during study for acetylated wood. Values with the same letter indicate that means between intervals do not differ significantly at $p < 0.05$. (**a**) color change (Δ*E*), (**b**) Δ*L**, (**c**) Δ*a**, (**d**) Δ*b**.

The most striking differences occurred for surfaces treated with HN between the two locations (Figure 10). For example, Δ*E* was higher on samples from the Corvallis location, whereas Δ*L** and Δ*b** were lower in Corvallis at the end of the study for this coating.

While only a few differences in *L*a*b** values were significant, there were changes in the visual appearance of acetylated wood specimens treated with the three coatings used in this study. Samples tended to lighten during the first two intervals and then darken during the last interval for samples located in Madras (Figures 11–13). This pattern was especially evident for surfaces treated with S1, which also experienced large decreases in Δ*L** and an increase for Δ*b** (Figure 9). In all cases, coatings appeared to degrade earlier on surfaces exposed in Corvallis than the same combination exposed in Madras. Mold was observed on very few samples exposed in Madras but was present on all surfaces treated with OM. In contrast, mold was observed on OM- and HN-treated surfaces much earlier on samples exposed at Corvallis.

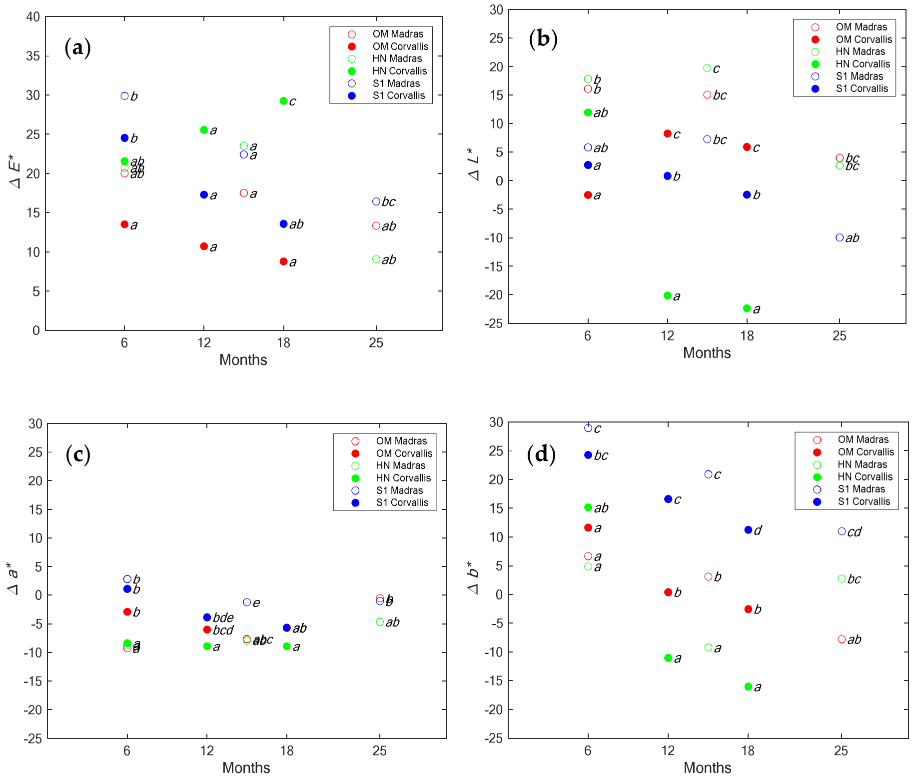

Figure 10. Games–Howell pairwise mean differences in Δ*E*, Δ*L**, Δ*a**, and Δ*b** for each species/coating combination from each location during study for acetylated wood. Values with the same letter indicate that means between intervals did not differ significantly at $p < 0.05$. (**a**) color change (Δ*E*), (**b**) Δ*L**, (**c**) Δ*a**, (**d**) Δ*b**.

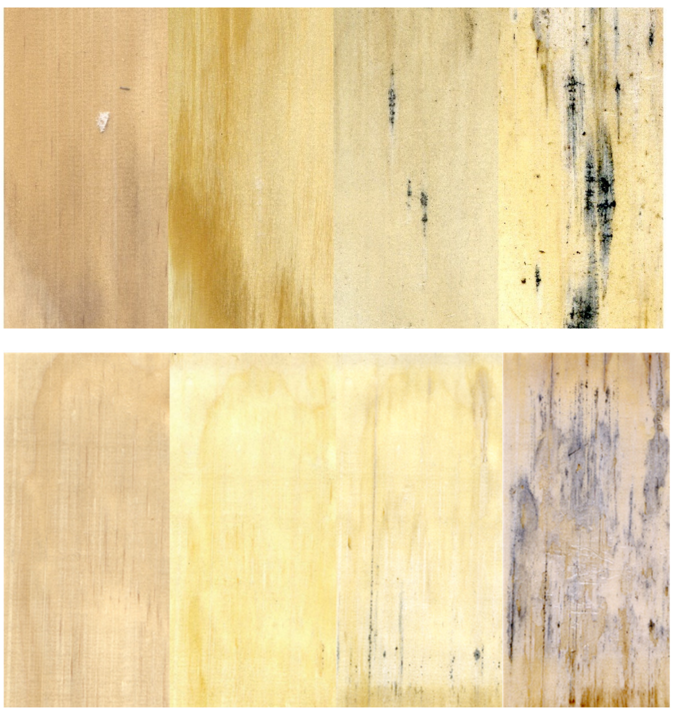

Figure 11. Examples of the same acetylated wood specimen treated with OM and exposed outdoors on a test fence near Corvallis, OR, for 0, 6, 12, and 18 months (**top row**) and a similarly treated sample exposed at Madras, OR, for 0, 6, 15, and 25 months (**bottom row**).

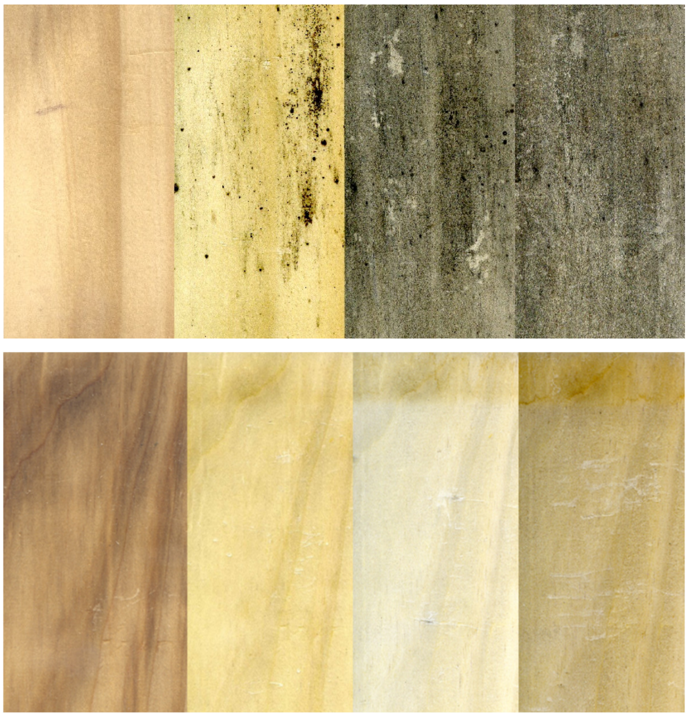

Figure 12. Examples of the same acetylated wood specimen treated with HN and exposed outdoors on a test fence near Corvallis, OR, for 0, 6, 12, and 18 months (**top row**) and a similarly treated sample exposed at Madras, OR, for 0, 6, 15, and 25 months (**bottom row**).

Figure 13. Examples of the same acetylated wood specimen treated with S1 and exposed outdoors on a test fence near Corvallis, OR, for 0, 6, 12, and 18 months (**top row**) and a similarly treated sample exposed at Madras, OR, for 0, 6, 15, and 25 months (**bottom row**).

4. Discussion

The objective of this study was to compare the performance of three commercial exterior coatings on two wood species in a semi-arid temperate climate and a warm-summer Mediterranean climate using the color change parameters of the CIELAB color system. This approach permitted integration of the non-uniform surface degradation across the sample rather than depending on isolated points on the sample and to integrate across differences between late and earlywood for Douglas fir, which displayed prominent differences between the two. This method is analogous to early studies that accessed color change visually [8,10], but provides a means to compare color change based on the information contained within digital images. The degree of darkening, coupled with increased green and blue contrast and coating degradation, indicated the coatings tested did not protect against color change due to weathering or mold growth after 15 months exposure in Madras or 12 months in Corvallis. Some coating/wood species combinations developed an acceptable uniformly weathered wood patina over the prolonged exposure, while other combinations developed unsightly blotchy discoloration.

The results are consistent with previous studies of both finished and unfinished wood, although the changes were not always consistent over time [4,7–10,26–30]. For example, ΔE indicated greater darkening (negative change in L^* between the initial and each sampling interval) during the first 6 months than for the next 9 months (Douglas fir treated with OM and HN). In other cases, changes in b^* indicated relatively uniform decreases between intervals.

In general, S1-treated Douglas fir samples experienced the least changes in overall color change during the first and second intervals in Madras while OM- or HN-treated acetylated wood experienced the smallest changes in the third interval. Douglas fir treated with the coatings tended to darken only slightly (as indicated by slight decreases in L^*), but then darkened dramatically during the final interval of the study. This can be expected because this was the longest interval during the study (10 months versus 6 months) and occurred during the winter (wet and cold) months. Color saturation increased for the green component and, to a greater degree, the blue component throughout the study. The coatings were cracking and peeling during the final exposure interval for Douglas fir surfaces treated with OM or S1, indicating that these coatings had largely failed by the end of the study.

While Douglas fir surfaces darkened slightly at the Madras location during the first two intervals of the study, acetylated wood lightened considerably as indicated by large differences in L^*. However, values were more comparable to those of Douglas fir at the end of the study. Mold was observed on surfaces treated with OM by the end of the study, indicating that the coating had lost its fungistatic value.

Coating performance appeared to be influenced by climate for a few of the coating/species combinations. The most distinctive differences were observed for OM-treated surfaces. For example, OM-treated Douglas fir surfaces darkened more when exposed at Corvallis than at Madras during the first and second intervals of the study, despite the longer exposure time for the Madras samples. Overall, saturation increased for red and yellow during the first and second intervals of the study. This pattern was also visible in the comparison images of each coating/species combination.

The film-forming coating (OM) appeared to peel earlier on Douglas fir at Madras, suggesting that the intense UV at this site degraded the coating and the underlying wood, leading to a graying effect in areas where the coating was removed. Conversely, mold was more abundant on areas where the coating had peeled at the Corvallis site, leading to a black, blotchy appearance. A similar pattern occurred for acetylated wood treated with HN; samples appeared black by the second interval in Corvallis but weathered to a more uniform patina at Madras. Douglas fir treated with HN weathered (little observable mold) significantly in Corvallis, but weathered far less in Madras, although the surfaces did show considerable checking by the end of the study. The pigmented coating (S1) resisted degradation better than the other two coatings on acetylated wood at both sites, although it retained a strong yellow/orange tint throughout the study. In contrast, S1-coated Douglas fir appeared to degrade significantly, leading to a blotchy appearance in Corvallis and a cracking/peeling appearance in Madras where the mold risk was lower.

Differences in both the rate of UV degradation of the coating and the potential for microbial attack will have important effects on coating performance. While no coating was completely effective at either site, the more severe UV exposure at Madras accelerated coating degradation while the wetter conditions at the Corvallis site were more suitable for mold attacks that lead to greater surface disfigurement. The differences highlight the need to tailor coating performance expectations to site conditions. This phenomenon could be interesting in an architecture context where a weathered appearance is desirable in the long term. While the limited number of samples restricted the statistical analysis and discussion, similarly treated samples experienced markedly different types of coating failures at the two sites, suggesting the need to consider exposure conditions when contemplating the final appearance of an exposed wood surface. Although the results did not produce hard-and-fast guidance by which to select one finish over another, the study suggests that coating selection should be a carefully considered act. A single coating formulation may not be suitable for all applications or exposure conditions. In addition, coating selection is a multifaceted decision that should include not only performance, but also environmental implications, ease of application, and color effects on different species.

It would be useful to repeat this trial using more coating/treatment combinations with more frequent assessments using combinations of the CIELAB system, visual assessment, and perhaps water repellency assessments. Although no attempt was made in this study to examine differences between earlywood and latewood, images of Douglas fir indicate differences in the rate of color change. Future work would benefit by analyzing this phenomenon separately to better understand coating performance on species with distinctively different growth ring characteristics.

5. Conclusions

This study confirms that different coatings provide different levels of performance against the effects of natural weathering when exposed to different climates. It also suggests that coating performance can depend on local environmental conditions and the selection of one coating over another should benefit from coating performance knowledge. The results may help to guide users wishing to specify coatings for exposed exterior applications and to predict the long-term appearance that would result from different coatings. Selection of the best coating will delay surface discoloration and reduce the maintenance required to retain the desired natural aesthetics of exposed wooden building elements.

Author Contributions: Formal analysis, K.D.; conceptualization and methodology, J.J.M.; conceptualization, supervision, and project administration, S.L.; writing—review and editing, K.D., J.J.M. and S.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing is not applicable to this article.

Acknowledgments: The authors would like to acknowledge the contributions of Matt Konkler for developing the exposure rack and placing and retrieving specimens; student workers Eliazar Lopez and Kathy Hu for their work preparing the test specimens; and Vikki Leavengood for scanning the specimens.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Flexner, B. *Understanding Wood Finishing: How to Select and Apply the Right Finish*; Reader's Digest: Pleasantville, NY, USA, 1999.
2. Evans, P.D.; Haase, J.G.; Seman, A.S.B.M.; Kiguchi, M. The search for durable exterior clear coatings for wood. *Coatings* **2015**, *5*, 830–864. [CrossRef]

3. Feist, W.C.; Hon, D.N.-S. Chemistry of weathering and protection. In *The Chemistry of Solid Wood*; American Chemical Society: Washington, DC, USA, 1984; pp. 401–451. [CrossRef]
4. Oberhofnerová, E.; Panek, M.; Böhm, M. Effect of surface pretreatment with natural essential oils on the weathering performance of spruce wood. *Bioresources* **2018**, *13*, 7053–7070. [CrossRef]
5. Rosu, L.; Mustata, F.; Varganici, C.; Rosu, D.; Rusu, T.; Rosca, I. Thermal behaviour and fungi resistance of composites based on wood and natural and synthetic epoxy resins cured with maleopimaric acid. *Polym. Degrad. Stab.* **2019**, *160*, 148–161. [CrossRef]
6. Rosu, L.; Varganici, C.-D.; Mustata, F.R.; Rusu, T.; Rosu, D.; Rosca, I.; Tudorachi, N.; Teacă, C.-A. Enhancing the thermal and fungal resistance of wood treated with natural and synthetic derived epoxy resins. *ACS Sustain. Chem. Eng.* **2018**, *6*, 5470–5478. [CrossRef]
7. Sarvis, J. *Exterior Clear Finishes*; Western Pine Association Research Laboratory: Portland, OR, USA, 1953.
8. Estrada, N. Exterior durability of catalyzed clear coatings on redwood. *J. Paint Technol.* **1967**, *39*, 655–662.
9. Fessel, F. Results of several years' weathering tests on surface-treated woods in exterior use in buildings. *Holzzentralblatt* **1966**, *92*, 257–261.
10. Ashton, H. *Clear Finishes for Exterior Wood, Field Exposure Tests*; Division of Building Research, National Research Council of Canada Ottawa: Ottawa, ON, Canada, 1967.
11. Davis, K.; Leavengood, S.; Morrell, J. Performance of exterior wood coatings in temperate climates. *Coatings* **2021**, *11*, 325. [CrossRef]
12. Borgin, K.; Gorbett, K. A Comparison of the Effect of weathering of paints, varnishes and water repellents as coating systems for wood. *S. Afr. For. J.* **1973**, *84*, 10–15. [CrossRef]
13. Browne, F.L. *Natural Wood Finishes for Exteriors of Houses*; F.S. U.S. Department of Agriculture: Madison, WI, USA, 1951; p. 9.
14. Miniutti, V. Microscale changes in cell structure at softwood surfaces during weathering. *For. Prod. J.* **1964**, *14*, 571–576.
15. Forest Products Laboratory. *Wood Handbook-Wood as an Engineering Material*; General Technical Report; U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: Madison, WI, USA, 2010; p. 508.
16. Zanetti, M.; Mothe, F.; Merlin, A.; Janin, G.; Moguédec, G.; Goncalez, J. Consequences of weathering on the users' aesthetic perception of oak wood (Quercus petraea (Matt.) Liebl.). *Ann. For. Sci.* **2003**, *60*, 61–68. [CrossRef]
17. Kropat, M.; Hubbe, M.A.; Laleicke, F. Natural, accelerated, and simulated weathering of wood: A Review. *BioResources* **2020**, *15*, 9998–10062. [CrossRef]
18. Konica Minolta, Inc. *Precise Color Communication: Color Control from Perception to Instrumentation*; Konica Minolta, Inc.: Tokyo, Japan, 2007.
19. Franklin, J.; Dyrness, C.T. *Natural Vegetation of Oregon and Washington*; Oregon State University Press: Corvallis, OR, USA, 1988. [CrossRef]
20. Old Masters. 2021. Available online: https://myoldmasters.com/documents/old-masters-spar-marine-varnish-tds (accessed on 1 December 2021).
21. Heritage Natural Finishes. 2021. Available online: https://www.heritagenaturalfinishes.com (accessed on 1 December 2021).
22. The Sansin Corporation. 2021. Available online: https://www.sansin.com/product/classic (accessed on 1 December 2021).
23. Weather Spark. 2021. Available online: https://weatherspark.com/y/1217/Average-Weather-in-Madras-Oregon-United-States-Year-Round (accessed on 3 November 2021).
24. Penn, A. Wanova. 2021. Available online: https://www.mathworks.com/matlabcentral/fileexchange/61661-wanova (accessed on 27 February 2021).
25. Trujillo-Ortiz, A. Ghtest. 2021. Available online: https://www.mathworks.com/matlabcentral/fileexchange/3676-ghtest (accessed on 27 February 2021).
26. Laskowska, A.; Dobrowolska, E.; Boruszewski, P. The impact of ultraviolet radiation on the colour and wettability of wood used for facades. *Drewno* **2016**, *59*, 99–111. [CrossRef]
27. Oberhofnerová, E.; Pánek, M.; García-Cimarras, A. The effect of natural weathering on untreated wood surface. *Maderas. Cienc. Tecnol.* **2017**, *19*, 173–184. [CrossRef]
28. Nzokou, P.; Kamdem, D.P.; Temiz, A. Effect of accelerated weathering on discoloration and roughness of finished ash wood surfaces in comparison with red oak and hard maple. *Prog. Org. Coat.* **2011**, *71*, 350–354. [CrossRef]
29. Sivrikaya, H.; Hafizoglu, H.; Yasav, A.; Aydemir, D. Natural weathering of oak (Quercus petrae) and chestnut (Castanea sativa) coated with various finishes. *Color Res. Appl.* **2011**, *36*, 72–78. [CrossRef]
30. Zgenç, Ö.; Durmaz, S. The comparison of weathering resistance of new generation wood-coating systems. In Proceedings of the IRG48 Scientific Conference on Wood Protection, Ghent, Belgium, 4–7 June 2017; pp. 1–9.