INSTITUTO TECNOLÓGICO DE COSTA RICA

VICERRECTORÍA DE INVESTIGACIÓN Y EXTENSIÓN

DIRECCIÓN DE PROYECTOS

ESCUELA DE INGENIERÍA FORESTAL

CENTRO DE INVESTIGACIÓN EN INTREGRACIÓN BOSQUE INDUSTRIA

INFORME FINAL DE PROYECTO DE INVESTIGACIÓN:

“Efecto de los acabados en la durabilidad de la madera de 10 especies provenientes de plantación forestal de rápido crecimiento”

Código 5402-1401-1014

DOCUMENTO Nº 2

Investigadora responsable:
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SETIEMBRE 2013

INSTITUTO TECNOLÓGICO DE COSTA RICA
VICERRECTORÍA DE INVESTIGACIÓN Y EXTENSIÓN
DIRECCIÓN DE PROYECTOS

INFORME FINAL DE PROYECTO

Datos Generales

1. Nombre del Proyecto: "Efecto de los acabados en la durabilidad de la madera de 10 especies provenientes de plantación forestal de rápido crecimiento**"** **Código 5402-1401-1014**

2. Departamento académico o Centro responsable: Escuela Ingeniería Forestal / CIIBI

3. Otras escuelas participantes: Escuela de Ingeniería en Electrónica y Escuela de Electromecánica

4. Investigadora coordinadora:

Nombre del(la) investigador(a) y grado académico	Jornada en el proyecto (hrs/sem)	Período	Nº de meses en el proyecto	Tipo de plaza
Ing. Cynthia Salas Garita	16 hr/sem	Del 1 de enero del 2011 al 31 de diciembre del 2012	24	DOC
	16 hr/sem	Del 1 de enero del 2013 al 30 de junio del 2013	6	REC

5. Investigadores colaboradores:

Nombre del(la) investigador(a) y grado académico	Jornada en el proyecto (hrs/sem)	Período	Nº de meses en el proyecto	Tipo de plaza*
Ing. Róger Mora Roque	4 hr/sem	Del 1 de enero del 2011 al 31 de diciembre del 2012	24	DOC
Ing. Diego Camacho Cornejo	8 hr/sem	Del 1 de enero del 2011 al 31 de diciembre del 2011	12	VIE
Ing. Lupita Vargas Fonseca	8 hr/sem	Del 1 de enero del 2012 al 31 de diciembre del 2012	12	VIE

6. Fecha de inicio formal de la actividad: **1 de enero del 2011**

7. Fecha de finalización formal de la actividad: **30 junio 2013**

8. Sesión y fecha de aprobación de Escuela: **Sesión Ordinaria 15-2013 del 30 de setiembre del 2013 Artículo 4 inciso 2.**

Cumplimiento de objetivos

Objetivo general: Determinar la efectividad, contra el deterioro de la madera, de diferentes acabados del tipo preservantes, disponibles en el mercado nacional costarricense, sobre 10 especies de plantaciones forestales de rápido crecimiento.					
Objetivos específicos	**Actividades**	**Productos**	**Fecha propuesta de cumplimiento**	**% de avance**	**Comentarios**
✓ Determinar el envejecimiento que sufren las diferentes especies de madera según sea el tipo de acabado aplicado, utilizando cámaras de interperismo acelerado.	Preparar las probetas por especie incluyendo dimensionado, lijado, y aplicación del acabado Exponer por 400 horas las probetas en la cámara QV Lab con ciclos de luz y condensación alternos Efectuar las evaluaciones de color y degradación a las probetas cada 24 horas para todas las especies	Curvas de envejecimiento acelerado en días por especie por tipo de acabado	Ene-Feb 2011 1 especie por mes empezando en marzo 2011 y terminando junio 2013 Se hacen cada 24 horas para 1 especie por mes empezando en marzo 2011 y terminando junio 2013	100 100 100	
✓ Determinar el envejecimiento que sufren las diferentes especies de madera según sea el tipo de acabado aplicado, en condiciones naturales de exposición a la intemperie.	Preparar las probetas por especie incluyendo dimensionado, lijado, y aplicación del acabado Exponer a la intemperie por 17 meses las probetas de cada especie Efectuar las evaluaciones de color y degradación a las probetas 2 veces por semana el primer mes y una vez por semanas los siguientes 16 meses.	Curvas de envejecimiento natural en días por especie por tipo de acabado	Ene-Feb 2011 Marzo 2011 2 veces/sem durante marzo 2011 y 1 vez/sem hasta agosto 2012	100 100 100	

Objetivo general: Determinar la efectividad, contra el deterioro de la madera, de diferentes acabados del tipo preservantes, disponibles en el mercado nacional costarricense, sobre 10 especies de plantaciones forestales de rápido crecimiento.

Objetivos específicos	Actividades	Productos	Fecha propuesta de cumplimiento	% de avance	Comentarios
✓ Establecer las comparaciones correspondientes entre estos dos métodos de de exposición a la intemperie para hacer las estimaciones sobre el envejecimiento y compararlas con muestras de madera de las mismas especies que no han recibido acabados.	Tabular los datos Efectuar los análisis Escribir los informes correspondientes a semestre y final de proyecto, Efectuar presentaciones y conformar material de divulgación	Análisis de varianza considerando las diferentes fuentes de variación Presentación de resultados en seminarios, boletines y publicaciones diversas	Actividad permanente desde marzo 2011 a setiembre 2012 Avanzar con los análisis por especie y entre especies cada vez que se completa una prueba desde abril 2011 hasta octubre 2012 Jun 2011 Nov 2011 Jun 2012 Dic. 2012 Oct 2011 Mar. 2012 Nov. 2012	100 100	I Informe en agosto 2011 II Informe en diciembre 2011 III informe en julio 2012 IV Informe en diciembre 2012 Informe final set 2013
✓ Establecer y clasificar los cambios visuales de foto-degradación y foto decoloración y su grado de afectación en el tiempo para las 10 especies analizadas para determinar cuáles acabados son mejores para prolongar la duración de la vida útil de la madera.	Tabular los datos Efectuar los análisis	Análisis de varianza considerando las diferentes fuentes de variación Presentación de resultados en seminarios, boletines y publicaciones diversas	Actividad permanente desde marzo 2011 a setiembre 2012 Avanzar con los análisis por especie y entre especies cada vez que se completa una prueba desde abril 2011 hasta octubre 2012 Jun 2011	100	

Objetivo general: Determinar la efectividad, contra el deterioro de la madera, de diferentes acabados del tipo preservantes, disponibles en el mercado nacional costarricense, sobre 10 especies de plantaciones forestales de rápido crecimiento.					
Objetivos específicos	**Actividades**	**Productos**	**Fecha propuesta de cumplimiento**	**% de avance**	**Comentarios**
	Escribir los informes correspondientes de semestre final de proyecto		Nov 2011 Jun 2012 Dic. 2012	100	Informe de avance hecho en agosto 2011, diciembre 2011, julio 2012 y diciembre 2012 Informe final en setiembre 2013
	Elaborar el material de presentaciones y divulgación		Oct 2011 Mar. 2012 Nov. 2012		

Cumplimiento del plan de difusión

La transferencia masiva de resultados de este proyecto no fue el objetivo primordial de la ejecución de proyectos aunque se reconoce que sobre la marcha se tenía presente este aspecto. Presentar resultados parciales no fue posible por las características del diseño de experimento.

1. Se escribió un artículo informativo para la revista Investiga Tec, la publicación de este es informativa y ya se presentó para su inclusión en número siguiente. Una copia del escrito enviado para la publicación se encuentra en el anexo 1 de este informe.
2. Se estará participando en el VI Encuentro de Investigación que se llevará en Cartago en Marzo 2014.
3. Se escribió un artículo científico que se está presentando en la revista "*Journal of Coatings Technology and Research"* Documento enviado en anexo 2.

Limitaciones y problemas encontrados

- La limitación más relevante sobre la ejecución del proyecto se presentó con las compra de repuestos, la traída de las lámparas desde el extranjero tardó más de 6 meses en todo el proceso. Esto a pesar de que no hubo limitaciones presupuestarias.
- Hacia el final del proyecto aprobado y faltando 3 especies de exponer en la cámara de envejecimiento acelerado se dañó un sensor de UV de la cámara y este sensor demoró en llegar 4 meses. Este aspecto repercutió en que debiera solicitarse una prórroga de 6 meses para poder concluir con las mediciones del proyecto. Aunque la prórroga fue otorgada, el tiempo apenas alcanzó para concluir con las mediciones.
- El manejo de la base de datos de este proyecto fue medular pues el total de las mediciones asciende a 60000 para todo el proyecto, lo que incluye mediciones de color, espesor de película, fotografías y efectuar la valoración de la norma de degradación se superficie. La VIE apoyó este manejo facilitando una computadora portátil asignada para proyectos de investigación que llegó en agosto del 2012.

Observaciones generales y recomendaciones

-El presupuesto total tuvo una ejecución aproximada entre el 85% y 90% la diferencia en ejecución la dio una donación de acabados que recibidos de grupo Kativo.

-Que haya un encargado de compras por Internet, en aprovisionamiento, que domine el inglés y que esté capacitado en las compras por este medio para que sea más ágil este proceso.

Anexo 1
Efecto de los acabados en la durabilidad de la madera

Ing. Cynthia Salas Garita, M.Sc
Escuela de Ingeniería Forestal

Las condiciones ambientales presentes en toda la franja tropical, por sus altas temperaturas y la presencia de precipitaciones, a lo largo del año, propician que en países como Costa Rica se puedan desarrollar una gran variedad de especies arbóreas maderables. Una gran cantidad de estas especies se han utilizado en programas de reforestación con fines comerciales.

Dentro de las especies nativas utilizadas en estos programas de reforestación se encuentran especies que son muy utilizadas en la fabricación de muebles y estructuras para uso exterior, entre esas especies se encuentra *Terminalia amazonia, Terminalia oblonga, Vochysia guatemalensis, Bombacopsis quinata, Alnus acuminata y Swietenia macrophylla y entre las especies exóticas como Cupressus lusitanica, Tectona grandis, Pinus caribaea y Acacia mangium*.

La madera producida por estas especies, por ser un material de origen biológico, siempre será susceptible a la degradación, pero cuando esa madera es utilizada en exteriores, esta queda expuesta a la radiación solar y al ambiente en general, donde los rayos ultravioleta y la humedad la degradan con mayor velocidad.

Para aumentar su estética y aumentar su vida útil, el mercado de pinturas nacional e internacional ha desarrollado una gran cantidad de productos acabados y productos en general como preservantes y tintes que pretenden aumentar la vida útil de la madera.

El estudio efectos de los acabados en la durabilidad de la madera pretende demostrar los niveles de degradación del color en la madera que utilizan acabados en relación con aquellos que no los utilizan así como evaluar la degradación de las superficies por aparición de eventos erosivos en las capas de acabado que se colocan en la madera, sean estos productos de la radiación UV o de la presencia de humedad.

Metodología

Para realizar el experimento se utilizaron 10 de las especies más utilizadas en reforestación comercial, entre ellas las 6 especies nativas y 4 especies exóticas mencionadas con anterioridad. Se utilizaron 3 acabados diferentes de los que comúnmente ofrece el mercado nacional en la línea de recubrimiento final, uno de ellos del tipo emulsión con color cedro y los otros dos del tipo poliuretano transparente, uno brillante y el otro satinado. Adicionalmente se utilizaron 4 diferentes tipos de preparación de superficie, según lo que comúnmente también se acostumbra en superficies exteriores; éstas consistieron en aplicar preservante, aplicar cera natural, aplicar preservante y cera y no aplicar nada, todo esto previo a agregar los diferentes tipos de acabado. Estos tratamientos fueron comparados con madera que no recibió ningún tipo de tratamiento. Las muestras de madera por especie se dividieron en dos grupos, la mitad de las piezas fueron expuestas 500 días a la intemperie natural y la otra mitad se expusieron en una cámara de envejecimiento acelerado durante 400 horas, donde se le aplicaron ciclos de radiación UV y condensación según la norma ASTM G- 154. Para ambos grupos de especies se realizaron mediciones de color utilizando un espectrofotómetro Hunter Lab Scan XE Mini Plus y el sistema cromatológico CIE Lab y para evaluar la degradación de la superficie se utilizó la norma ASTM D - 660, la cual permite evaluar la degradación de la superficie, además se ha evaluado la presencia o no de burbujas, hongos y manchas en los diferentes tratamientos.

¿En qué etapa estamos?

Nos encontramos en la etapa de análisis de resultados. Donde se pretende la generación de al menos un artículo para revista indexada.

Preliminarmente podemos indicar que se están evaluado el nivel de degradación tanto de la superficie como del color de la madera, producto de la exposición a la intemperie, donde se observa el efecto obvio de la presencia de los acabados. Está por demostrarse si efectivamente estos acabados aumentan la vida útil de los productos de madera y cuál es la dependencia de estos al repinte o retoque.

¿Quién financia?

Este proyecto de investigación ha sido financiado en su totalidad por la Vicerrectoría de Investigación y Extensión y se agradece la colaboración a Grupo Kativo quien facilitó muestras de acabados para el análisis.

Participantes

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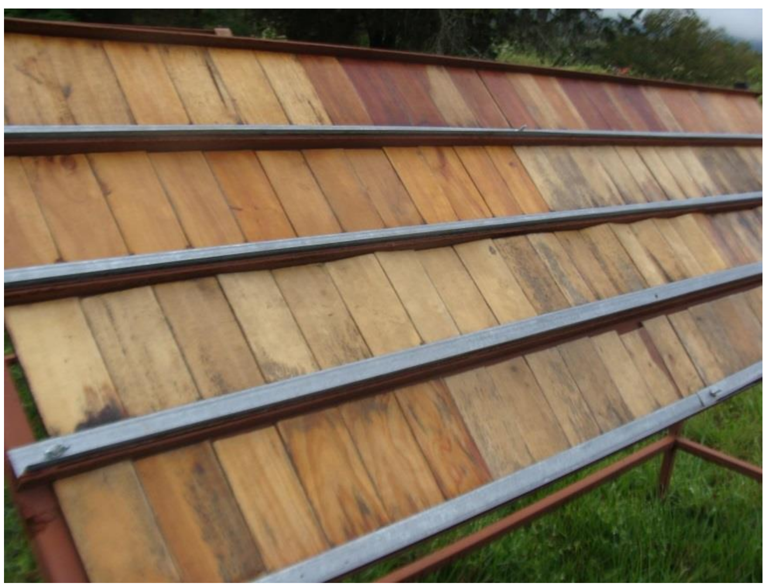
Ing. Roger Moya Roque, Ph.D

Ing. Lupita Vargas Fonseca

Ing. Diego Camacho Cornejo, M.B.A.

Medición del color de las muestras expuestas
en la cámara de envejecimiento acelerado



Muestras expuestas a la intemperie natural
después de 4 meses de exposición

Muestras expuestas a la intemperie natural
después de 4 meses de exposición

Muestras expuestas en la cámara de envejecimiento acelerado

Anexo 2. Artículo científico que ya se sometió a consideración para la publicación en la revista "*Journal of Coatings Technology and Research*"

Performance of three finishes on surfaces previously treated with wax and preservative in ten tropical plantations species wood in natural and accelerated weathering

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Performance of three finishes on surfaces previously treated with wax and preservative in ten tropical plantations species wood in natural and accelerated weathering

Abstract

This study evaluated wood color change (*ΔE**) and the surface quality in ten tropical wood protected with three finishes (based in wax and polyurethane) and coatings development for tropical conditions in natural (NW) and accelerated (AW) weathering condition. The results showed that the application of these finishes, decreased lightness (L*), increased the redness (a*) and yellowness (b*) parameters in all species. ΔE* values found in different finishes and coatings are cataloged as total change of color. It was found that NW produced the higher ΔE* and defects in the coating than AW. Other important results was that tropical clear wood with natural coating produces the higher ΔE* than dark wood color. L* and b* parameters were the most significantly effects on ΔE* of coatings, but any treatments of surface of wood L*, a* and b* affects ΔE*. The stains and fungal development was observed in polyurethane finishes in NW, but not AW. The irregular and mosaic flaw were not observed. The quality index created, which includes long and short line and switch flaw was lowest in NW and was lowest in waxy finish and the highest polyurethane finish.

Key words: Lab color systems, color change, surface quality, tropical wood, finishing, coating

Introduction

The environmental conditions characteristic of tropical regions, such as high temperature and rainfall throughout the year, as is the case of Costa Rica, enable the development of a great variety of forest plantation timber species.[1] Many of these species have been successfully used in reforestation programs with commercial purposes,[2] among them, native species like *Terminalia amazonia, Terminalia oblonga, Vochysia guatemalensis, Bombacopsis quinata, Alnus acuminata and Swietenia macrophylla*; *and* exotic species such as *Cupressus lusitanica*, *Tectona grandis*, *Pinus caribaea and Acacia mangium.*[3]

However, according to Moya and Muñoz[4], the lack of knowledge about the chemical properties, drying, preservation, natural durability of the wood, as well as resistance or color change of the finish applied, has been an obstacle in the utilization of the above mentioned tree species for commercial reforestation. Studies have been initiated recently on the physical and mechanical properties of these species[4], their behavior during the drying process,[5] and also the energy evaluation.[6]

On the other hand, plantation species have gained importance in the market of products for finishing (chemical products), which seek to protect the color and quality of the wood surface.[7] There are currently two large paint factories in Costa Rica (http://www.pinturassur.com/http://www.gruposur.net/ and http://www.grupokativo.com/), and other smaller ones that produce finishing and coating for wood, among other products. Such products are distributed and used from Mexico to Panama, where tropical species coming from forest plantations are currently used.

The paint factories have developed finishes for the tropical region, to protect the wood from the intensity of the ultraviolet rays (UV), the high relative humidity and the high levels of precipitation characteristic of the region. The polyurethane type finishes stand out for the protection of wood for exteriors. These are organic compounds of the urethane prepolymer type, water insoluble and UV light refractive, to reduce weather effects and maintain the quality of the color and of the surface in the long term.[8,9] As for oil finish, it can be dissolved in water, offers UV ray protection and is water repellent, thus preventing damage to the wood surface.[8,9]

One of the limiting factors of the finish on the wood when exposed to weather effects (color and degradation), is the degradation of the surface.[10] Factors such as solar radiation, temperature, rain, wind, relative humidity, heat, pollution and others, accelerate the process of discoloration and deterioration of the finish.[7,11] Various studies[7,12,13] have found that the UV light, visible light and the infrared light generate most chemical reactions in the wood components and in the finish itself.

The studies on the deterioration of the finishing on the wood surface usually focus on temperate wood species. Among the most evaluated species are: *Betula pendulata*,[13] *Cryptomeria japonica*[14] and *Picea* albies.[7,12,13,15] Due to this orientation, many factories use wood species from temperate climates to establish the characteristics of the finish they produce. In fact, Costa Rican factories use *Pinus radiata* as a standard for studies on the performance of wood finish. However, there are a few studies on the performance of finish for tropical woods, such as studies on *Cedrela odorata*, *Carapa guianenesis*, *Tectona grandis* and *Acacia mangium*,[16,17] which consider the performance of various finishes in natural and accelerated weathering conditions.

In view of this situation, it is important to understand the behavior of tropical species from fast growing plantations regarding color change and degradation of the coating on wood exposed to weathering conditions (natural or accelerated), when finishes produced for tropical conditions are used, so as to adequately orient the possible uses and markets for those species with the convenient finish. Therefore, the present research studies the initial color change when applying 3 different types of coating and finishing formulated for tropical conditions to 10 plantation species growing in such conditions (*Acacia mangium*, *Alnus acuminata*, *Bombapcosis quinata*, *Cupressus lusitanica*, *Gmelina arborea*, *Pinus caribaea*, *Swietenia macrophylla*, *Tectona grandis*, *Terminalia amazonia* and *Terminalia oblonga*). Also, the present study determines the color change and deterioration of the finish in wood exposed to accelerated and natural weathering conditions of these 10 wood species, for the different coatings and finishing.

Materials and methods

Site, plantation description, and tree sampling: ten different pure plantations located in several parts of Costa Rica were studied. The initial planting density was 1,111 trees/ha (3x3 m spacing). At the time of evaluation, the average age was 9-18 years old and the density was at 495-575 trees/ha. As explained in detail by Moya et al.,[5] the samples for the finishing trials were extracted from 25 mm thick boards dried to 12 % moisture content in conventional kilns. All these species are being introduced in the production of outdoor furniture. Twelve boards were used for each species.

Surface preparation and application of finishes and coating: Conditioned samples were polished with sandpaper #80 and subsequently with #120 and #220. Three types of outdoor finishing were used (Table 1), selected from those widely used in Costa Rica. Prior to the application of the three types of finishes, the surface wood was prepared with 4 different coatings also used in the tropics (Table 1). Therefore, 12 different treatments were applied to each species, while all species were compared to control samples, which corresponded to wood without coating or finishing application (Figure 1). After the application of the finishing and the surface treatments, the film thickness changed from 50 to 100 µm.

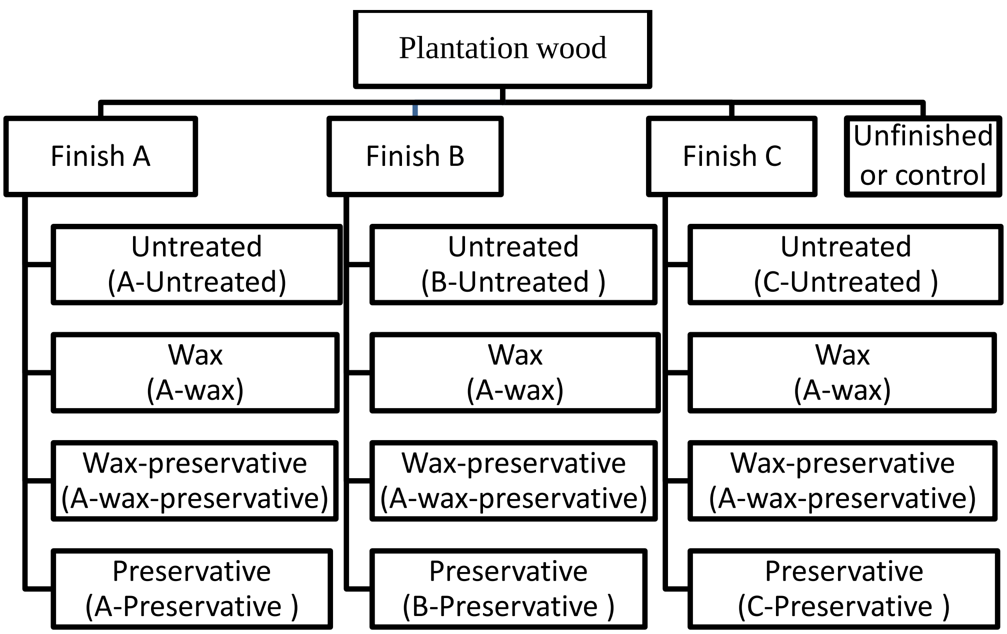

Figure 1. Finishes and coating applied on the surface of ten tropical species wood from plantations.

Note: Name in parenthesis represents the abbreviation utilized in the article.

Table 1. — Finishes studied and coating utilized on the surface of ten tropical species wood from plantations.

Type	Products	Description
Finishes	A	Water base, fast dry, protects against damage caused by moisture,

		and ultraviolet rays, and provides a mildew-resistant finish that won´t crack, peel or flake. The finishes were applied with a spreading rate of 3.7 m^2/liters. Color: cedar, nonvolatile content: 45% and application method: brush
	B	One component polyurethane (urethane prepolymer) finish for one step application on exterior. The finish was applied with a spreading rate of 14.7 m^2/liters. Color: clear gloss, nonvolatile content: 50% and application method: spray
	C	One component polyurethane (urethane prepolymer) finish for one step application on exterior. The finish was applied with a spreading rate of 14.7 m^2/liters. Color: clear satin, nonvolatile content: 50% and application method: spray
	Unfinished or control	The surface was left as it is
Coating	Wax	Natural oil modified for exterior condition. It protects against insects, fungal decay and UV radiation. Color: clear, nonvolatile content: 80% and application method: flannel.
	Preservative	Water base, no color, no odor, protects against insects, fungus and rot fungus. Color: clear, nonvolatile content: 80% and application method: brush.
	Wax-preservative	Preservative was added on the wood surface and the wax was added after 24 hrs. Color: clear, nonvolatile content: 80% and application method: brush-flannel.
	Untreated	Finishes were applied without any previous treatments on wood surface.

Sampling: 104 units of 15 x 7.5 x 0.6 cm were extracted from the 12 dried-lumber per species. These samples were conditioned at 12% moisture content (22 ºC temperature, and 67% relative humidity) prior to the application of the different finishes and coating. 4 units were tested in each treatment, which means a total of 104 samples per species (3 finishes x 4 surface treatments x 4 units + 1 control sample x 4 units). The samples were selected without damages and flaws and only heartwood was considered. Finally, the samples were conditioned at 12% moisture content (22 ºC temperature, and relative humidity of 67%) for 4 weeks. Then all finishes and coating were applied.

Time and weathering exposure characteristics: In this study, two kinds of exposure were tested: natural and accelerated. Natural weathering (NW) consisted on exposure to the elements, in an area free of shade and where the rain, sun and wind impacted directly on the samples. For the NW, samples were placed on anvils during a total time span of 500 days with an inclination of 45º. Wood samples were exposure in Cartago state of Costa Rica (9°50'59"N; 83°54'37"W). The site has an altitude of 1380 m.a.s.l with an annual temperature between 15.0 and 23.9 ºC and an average precipitation of 1563.5 mm. The solar radiation in Cartago state is 17 MJ/m^2. The climatic conditions were widely by Valverde and Moya.[17] For the accelerated weathering (AW), a weathering Q-Lab camera was used (QUV/spray model). The ASTM G-154 standard was applied for this test.[18] The exposure was of 4-hour cycles in two phases: first, 4 hours of UV radiation at 50ºC and a radiation of 0.71 W/m^2 (with mercury bulb type UVB 313 L and wave length 310 nm), then a second phase of condensation which took two hours and consisted of using evaporated water at a 50ºC temperature. The total exposure time was of 400 hours for each species.

Color determination: This wood characteristic was measured before and after weathering exposure on surface of finish. This means that all samples of NW were measured the color immediately after coating application, meanwhile surface color of all samples of AW were measured before that weathering began. Then a lapse time between coating application and color measuring was presented in these samples. Color measuring was done with a Hunter Lab mini Scan XE Plus spectrophotometer. The CIE Lab standardized chromatologic system was used. The range of this measurement is from 400 to 700 nm with an opening at the point of measurement of 11 mm. For the observation of reflection, the specular component (SCI mode) was included at a 10º angle, which is normal for the specimen surface (D65/10); a field of vision of 2º (Standard observer, CIE 1931) and an illumination standard of D65 (corresponding to daylight in 6500 K). The mini Scan XE Plus generated three parameters for each measurement, namely: L*(luminosity), a* (tendency of color from red to green), and finally b*(tendency of color from yellow to blue). The color of sample surfaces was measured at room temperature in two different measuring, each one at 2 cm from the ends. The measurement of color was evaluated in the UV radiation phase to avoid measurement errors for the condensation in AW. Wood samples in NW were evaluated between the 10th and 12th hour in the morning and without any event of rain before the measurement.

Color change (ΔE^*)**:** It was determined for three conditions: (i) color difference between unfinished and finish treatment in each wood species, (ii) color difference between untreated surface and coating treatment in each finish and each specie and (iii) color change for each finish between after and before weathering exposure. These differences were determined according to the ASTM D 2244 standard norm whose formula is detailed in equation 1.[19] To cataloged the ΔE^* color variation, Cui *et al.*[20] method was used. It establishes five color change levels perceived by the human eye: if $0 < \Delta E^* > 0.5$ the color change is not perceived by the human eye; if $1.5 < \Delta E^* > 3.0$ the color change is barely perceived; if $3.0 < \Delta E^* > 6.0$ the change is perceived; if $6.0 < \Delta E^* > 12.0$ the color change is quite noticeable by the human eye, and finally, if ΔE^* is higher than 12, there is a total color change.

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

Where:

ΔE^*= wood color difference; ΔL= L*before weathering - L*after weathering; Δa= a* before weathering - a* after weathering; Δb= b* before weathering - b* after weathering

Evaluation of the quality of surface with finish: after 500 exposures (NW or AW), the presence or absence of fungi, stains or bubbles on finished surface were evaluated. Fungi and stain presence were evaluated by the presence or not, whereas the presence of bubbles was crack of finish film on the wood surface. As well as, the evaluation of the quality of finish in each species and their behavior to weathering (NW as well as AW) the ASTM D-660 standard[21] was used, which establishes an evaluation system for the different kinds of deterioration that finishes face: irregular, long line, short parallels, mosaic and switch. In general, deterioration is evaluated on an even scale from 10 to 2, which, as the number reaches 2 it means a greater deterioration of the finish.

Statistical analysis: surface color parameters of finish (L* a* b*) of each species was analyzed before exposure to weathering. This analysis was considered the differences between control and each treatment of finishes and coating applied. A one-factor (one-way-Anova) analysis of variance per specie was applied to finish color parameters. The model included the following sources of variation: finishing (w), coating treatment (c), the interactions between weathering and coating treatment (Equation 2). The difference between the averages was assessed through Dunnett's test with a level of significance of

P<0.05, where a control treatment is wood samples without any finishing or coating. As well as, the effect of the change in color parameters (ΔL*, Δa* y Δb*) on total color change (AE *) was evaluated using multiple regression (Equation 3) for on the surface of wood with different finishes. Each parameters change in the regression was assessed using a significance level of 99%.

$$Y_{ij} = \mu + f_i + c_j + f * c_{ij} + e_{ij} \qquad (2)$$

$$\Delta E^* = \Delta L + \Delta a + \Delta b + \varepsilon rror \qquad (3)$$

where Y_{ij} is the single observation of each color parameter of the ij-wood sample, μ is the overall mean, *f* is the i_{th}-finishing type fixed effect, *c* is j_{th}-coating treatment fixed effect, $f*c_{ij}$ is the random interaction between the i_{th} finishing type and the jth coating treatment, and e_{ij} is the residual random effect.

Regarding the quality of finishes with different coating, firstly the presence or not of fungus, stain or bubbles were expressed percentage of presence in relation to total sample of finishing and coating. Second the quality index of degradation (IQ) was developed and it considers the 5 types of flaws evaluated under the ASTM D-660 standard,[21] considering irregularities, long lines, short parallels, switch and mosaic. The ponderation considered the importance of flaws appearances, the long lines surface being the one with the highest ponderation (50%), and then short lines (25%), switch surface (15%) and finally irregular surface (10%). The mosaic flaw was not considered in this index because this flaw was not observed in any sample. Subsequently, SQI behavior was evaluated with exposure time in NW and AW using equation 4.

$$SQI = (IR * 0{,}10) + (LL * 0.50) + (SP * 0.25) + (SS * 0{,}15) \qquad (4)$$

Where: IR: Irregular flaw; LL: Long Line flaw; SP Short Parallel flaw; SS: Switch flaw.

Results

A. Initial surface color of wood

Wood color was different for each species and type of finish. However, in all species, the L* parameter was above 35, varying from 35 to 70; the a* parameter was in all cases positive, varying from 9 to 24, and the b* parameter was also positive, varying from 15 to 50 (Figure 2). For the L* parameter, *A. mangium*, *S. macrophylla* and *T. grandis* registered the lowest values (Figures 2a, 2g and 2h), whereas the rest of the species presented average values for L*, higher than those for the previous species. Regarding the a* parameter, the lowest values are for *G. arborea*, *P. caribaea* and the two *Terminalia* species (Figures 2o, 2p, 2s and 2t). On the other hand, *S. macrophylla* presents the highest values (Figure 2q). Lastly, the b* parameter shows no differentiation among the various species (Figure 2u-1ad).

The initial wood color between the wood used for natural weathering (NW) and accelerated weathering (AW) was slightly different for the b* color parameter. In all species, the a* parameter was higher for the wood used in AW (Figure 2u-2ad). The other two parameters were similar in general, except for some species that presented some differences. For example, for *B. quinata* (Figure 1c and 1m), *G. arborea* (Figure 1e and 1o), *T. grandis* (Figure 2h and 2r) and *T. amazonia* (Figure 2i and 2s), L* and a* parameters showed higher values in the NW samples.

The application of the different types of finish or coatings affects the wood color parameters, in all wood species. The L* parameter was observed to decrease with the application of the finish in all species, in both types of weathering, except *G. arborea* with the treatment C-preservative (Figure 2e) in NW; *P. caribaea* with the treatments C-wax, C-wax-preservative and C-preservative in NW (Figure 2f) and *T. grandis* in treatments with the finish C (Figure 2h). Meanwhile, the a* parameter increased with the application of finishes to the wood, except in some cases where differences were not observed, such as *B. quinata* and *P. caribaea,* with finishes B and C (Figures 2m and 2p) and in *T. oblonga* in treatments with C-wax and C-wax-preservative (Figure 2t) and *T. grandis* in B-untreated and C-wax-preservative (Figure 2r). With regard to the yellow color parameter b*, it was found that this value increases in most of the species and conditions, with the exception of *S. macrophylla* with the finish A in NW and A-wax-preservative and A-preservative in AW treatments (Figure 2aa).

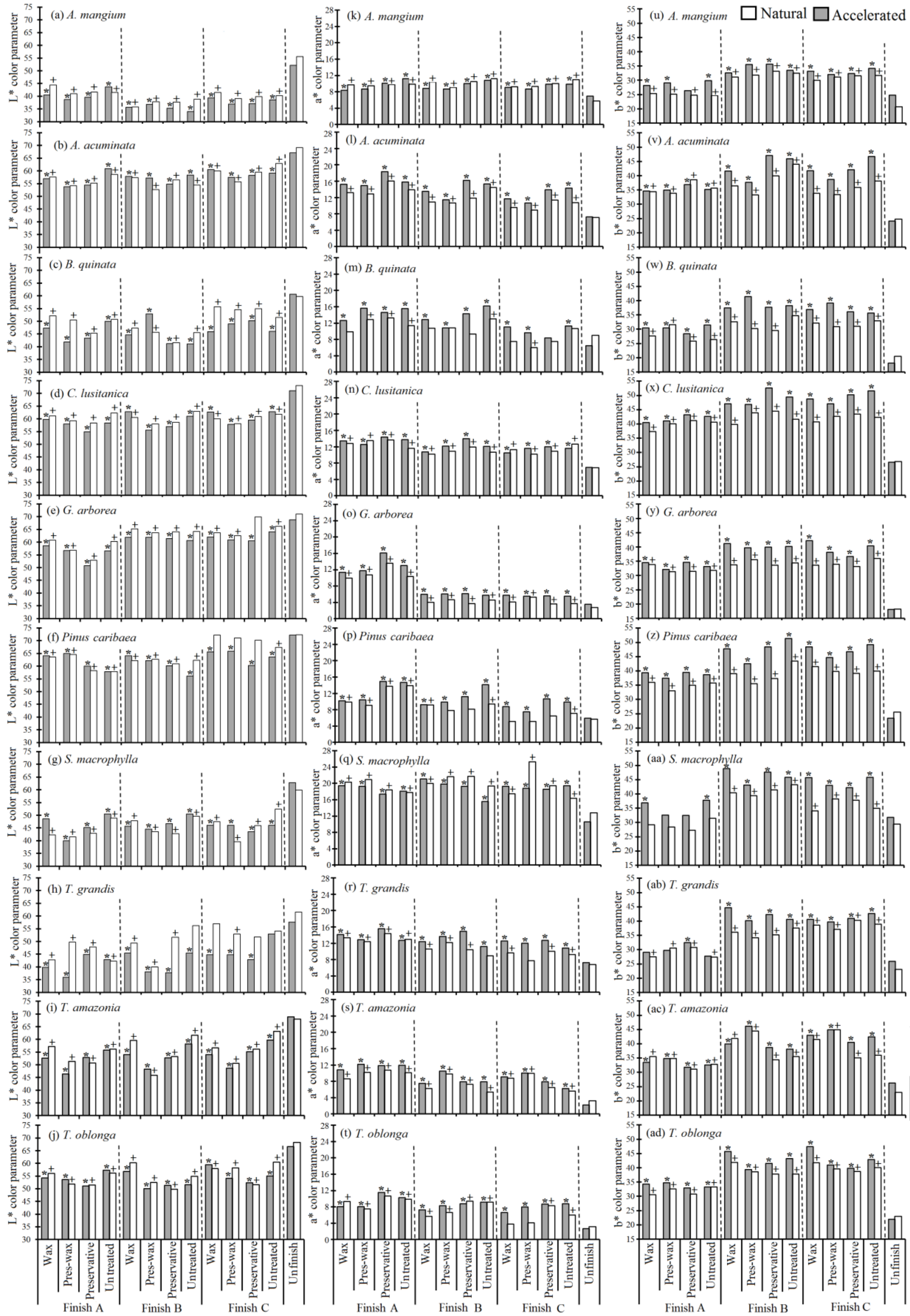

Figure 2. Initial values for the color parameters L*, a* and b* of the wood of 10 plantation species in Costa Rica, with 3 finishes and different surface treatments.

Figure 2 shows some differences in the various types of finishes. For example, in all species the b* parameter of finish A presents lower values than for finishes B and C (Figure 2u-2ad). Parameter b* shows no clear trend in the various types of finish. For example, finish A presents higher values of b* (Figure 2a), whereas its performance is irregular for the other species. Regarding the a* parameter, again no difference is observed between the various types of finishes and the different species (Figure 2k-2t).

In relation to the values obtained for the color change (ΔE*) in the two types of aging, the values varied from 10.9 to 31.1 (Table 2). *A. mangium* showed the lowest ΔE*, while the highest values occur with *B. quinata* and *P. caribaea* (Table 2). Also noticeable is the fact that the ΔE* values are higher than the values observed in AW for *A. mangium*, *B. quinata*, *C. lusitanica*, *G. arborea*, *P. caribaea*, *T. grandis*, *T. amazonia* and *T. oblonga*. For the other species (*A. acuminata* and *S. macrophylla*), the value of ΔE* for finished wood in NW, is higher than for the wood in AW, but not for all finishes.

On the other hand, ΔE* values for all of the species are in general lower for the wood with finish A, followed by finishes C and B, with few differences between them (Table 2). Moreover, most color changes (ΔE*) occurred in AW, using the 3 types of finishes for all species.

B. Color change due to exposure

ΔE* represents color change between the color of the wood before and after exposure. As expected, the highest change in all types of finishes and surface treatments for all species was in the samples exposed to NW. Similarly, ΔE* values were higher than 12 for all species and types of finishes with NW exposure (Figure 3).

Table 2. Color change (ΔE*) of the wood surface due to the application of the different finishes and coating in 10 plantation species in the tropics.

Finishes	Coating	*Acacia mangium*		*Alnus acuminata*		*Bombacopsis quinata*		*Cupressus lusitanica*		*Gmelina arborea*		*Pinus caribaea*		*Swietenia macrophylla*		*Tectona grandis*		*Terminalia amazonia*		*Terminalia oblonga*	
		Nat	Ac	Nat	Ac	Nat	Ac	Nat	Ac	Nat	Ac	Nat	Ac	Nat	Ac	Nat	Ac	Nat	Ac	Nat	Ac
A	Untreated	11.1	11.4	16.1	15.4	14.3	20.0	17.3	21.8	17.6	21.8	21.7	22.8	15.9	15.9	17.3	16.4	16.6	17.7	17.7	16.5
	Wax	10.9	12.3	15.3	16.7	13.6	19.9	16.1	19.6	19.0	20.8	16.1	18.7	23.1	17.7	17.1	19.8	16.6	19.9	15.5	19.2
	Preservative	11.2	13.0	20.7	21.3	18.5	21.8	20.6	24.4	23.1	27.7	19.9	22.2	22.0	19.1	14.2	17.9	20.8	19.7	19.4	21.0
	Wax+preservative	11.5	14.2	17.2	18.9	19.4	24.8	19.2	20.6	19.2	20.2	12.7	16.7	24.0	24.8	13.3	23.8	22.2	26.3	19.3	19.2
B	Untreated	16.1	20.6	24.9	25.0	24.8	30.0	17.8	25.7	17.1	23.5	22.9	33.5	19.7	20.7	14.4	23.5	12.2	17.2	21.1	26.9
	Wax	18.0	18.8	16.3	21.1	20.7	26.6	17.2	22.7	16.0	24.3	19.5	26.0	19.8	26.7	15.8	24.1	18.7	21.1	21.3	26.4
	Preservative	16.7	20.1	19.8	27.8	22.6	29.0	22.5	30.5	16.2	23.1	18.8	29.0	25.1	24.5	14.6	27.1	18.4	21.5	24.9	25.8
	Wax+preservative	16.2	19.2	17.6	17.4	20.1	25.7	22.2	26.2	18.2	23.0	16.3	22.3	23.7	23.6	20.6	25.2	31.1	30.0	23.1	24.9
C	Untreated	15.0	16.6	15.1	25.2	18.4	23.9	19.5	26.8	18.1	23.0	17.6	27.5	13.1	24.4	17.0	20.4	12.0	19.1	19.9	24.8
	Wax	12.4	15.2	12.5	19.4	15.8	24.8	18.6	24.0	16.5	25.3	18.1	26.1	17.3	24.1	14.4	21.4	20.8	23.6	22.4	26.8
	Preservative	14.2	17.3	14.6	21.2	15.2	22.0	20.2	26.9	15.2	20.6	16.0	27.0	20.1	24.0	17.7	22.7	16.2	20.7	24.1	24.0
	Wax+preservative	14.6	16.9	15.3	18.0	14.3	24.6	21.3	25.6	17.1	22.0	16.5	22.7	28.5	22.0	14.3	19.8	27.4	28.9	20.0	23.6

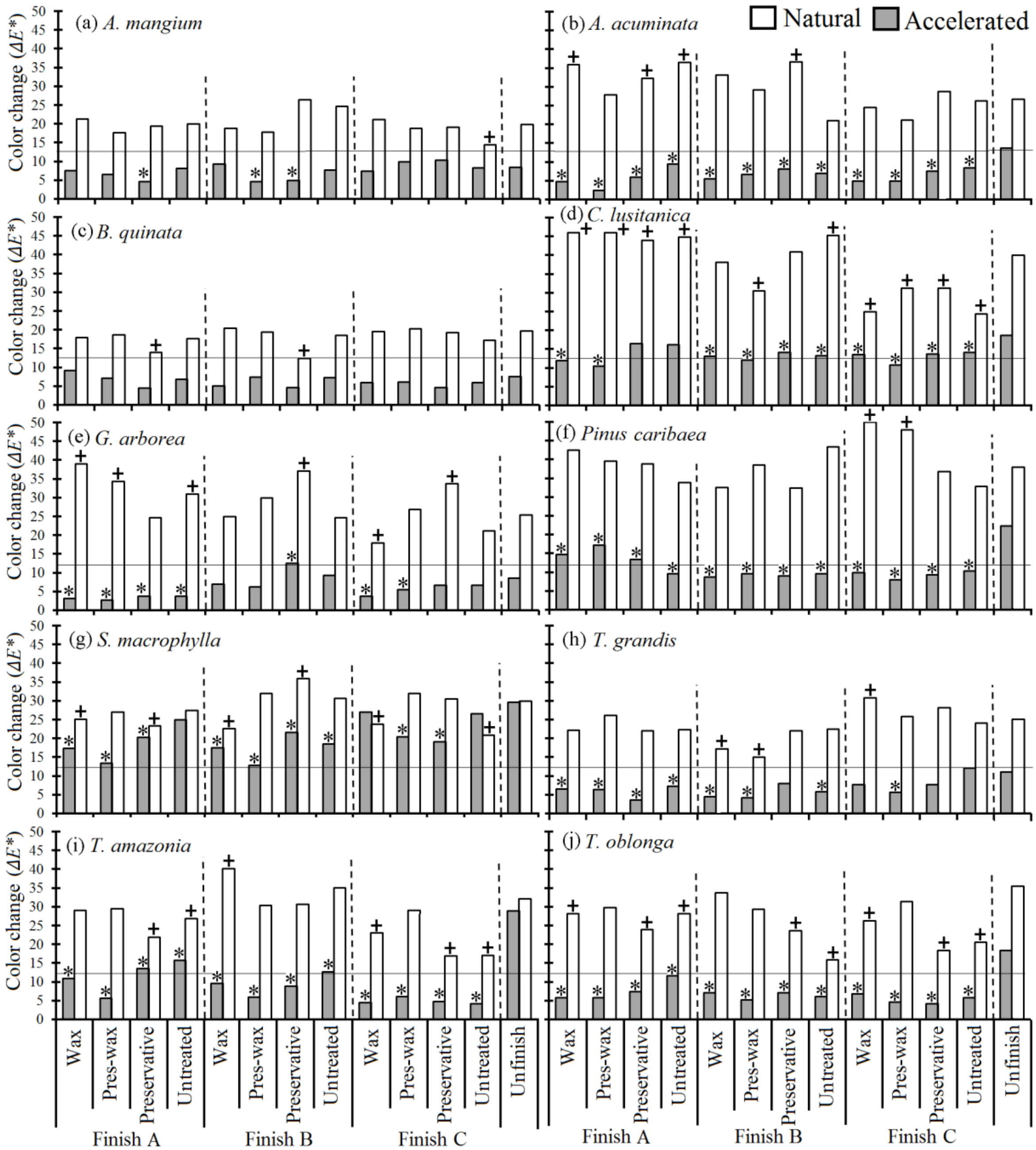

Figure 3. Color change (ΔE*) values of 3 types of finishing exposed to natural and accelerated weathering in 10 wood types from forest plantations.

The highest surface color changes, given by high values of ΔE*, for the different species in NW, were observed with the species *A. acuminata*, *C. lusitanica*, *G. arborea*, *Pinus caribaea*, *S. macrophylla*, and the two *Terminalia* species (Figure 3b, 3d-g, 3i and 3j). *A. mangium*, *B. quinata*, and *T. grandis* (Figures 3a, 3c and 3h), on the other hand, presented the lowest ΔE*, therefore the smallest color change compared to the previous group of species.

In AW, the highest ΔE* values, above 12, were found in *S. macrophylla* (Figure 3g), followed by *C. lusitanica* with ΔE* values close to 12 (Figure 3d). *T. amazonia* presents values lower than 12 in the treatments A-wax and A-preservative, A and B without treament and the control sample (Figure 3i). Some treatments with values over 12 are also observed in *P. caribaea*, specifically with the A finish and the control sample (Figure 3f). *T. grandis* and *T. oblonga* present values lower than 12 in most treatments except the control sample (Figures 3h and 3j). Lastly, *A. mangium*, *A. acuminata*, *B. quinata* and *G.arborea* present ΔE* values under 12 in all treatments (Figures 3a-c and 3e).

Concerning the ΔE* of the different types of finishing (A, B and C) and the coatings applied (wax, preservative-wax, preservative), compared to the control sample after exposure to weathering conditions, AW was found to produce the highest quantity of statistical differences among the species (Figure 3), except for *B. quinata* which showed no differences (Figure 3c), and *A. mangium* and *G. arborea* (Figures 3a and 3e), which presented few differences with the control sample.

Regarding NW, it depended on the species. For A. *mangium*, a lower ΔE* was found only in the treatment C-untreated (Figure 3a), while *P. caribea* presented ΔE* values for C-wax and C-preservative that were higher than for the control (Figure 3f). *A. acuminata* showed higher ΔE* values in the treatments with finish A, except for A-wax-preservative (Figure 3b). *B. quinata* showed significantly lower values in finishes A and B in the treatments with preservative (Figure 3c). *C. lusitanica* was the species with most statistical differences, compared to the control sample, all treatments with finish A presenting higher ΔE* value; contrary to finish C, which is lower (Figure 2d). In the case of *G. arborea*, the highest values are found in finish A in all treatments, except in the treatment with preservative, which in finishes B and C, however, presented ΔE* values statistically higher than the same value for the control sample (Figure 3e). Regarding *S. macrophylla*, the ΔE* in treatments with wax and C-untreated was statistically lower, while for the B-preservative treatment it was statistically higher (Figure 3g). *T. grandis* also presented few differences with the lowest values of ΔE* in B-wax and B-wax-preservative, and the highest value in C-wax (Figure 3h). In the treatments where differences were found, the ΔE* for *T.*

amazonia was lower, except for B-wax (Figure 3i). In the case of *T. oblonga*, when differences were found, the ΔE* was lower, as well as in treatments with preservative or only with the finish, without coating (Figure 3j).

The ΔE* of the surface of the finish after exposure, is influenced by the color parameters. The analysis of this influence by means of a multiple regression (Equation 3), showed that (Table 3):

1. For the control sample (without finish), the ΔE* is significantly affected by the luminosity (L*) and the tonalities of red (a*) and yellow (b*) in the 10 species and in the two types of exposure, except for *A. mangium*, affected only by L*and B*; for *T. grandis* in NW, the ΔE* affected L* and in AW affected a* and b*; for *G. arborea* in NW, the L* and b* parameters were affected.
2. The L* parameter significantly affected ΔE* in most treatments, except for: (i) *A. mangium* in A-wax-preservative in NW: (ii) *B. quinata* in B-wax and C-untreated in AW; (iii) *G. arborea* and *P. caribaea* in B-wax-preservative in AW; (iv) *S. macrophylla* in C-wax and C-wax-preservative in AW and the treatments C- wax and C- preservative in NW, (v) *T. grandis* in A- wax, and A- preservative in NW and in the treatments C- wax and C- preservative in AW; (vi) *T. amazonia* in AW in treatment C- wax and (vii) *T. oblonga* in AW in the treatments B-untreated and C- untreated and in NW in the treatment C- preservative.
3. The ΔE* value was significantly affected by L* and b* together in many of the species and types of finish, for example, in the species *T. amazonia*, with finishes B and C.
4. In those cases that the luminosity parameter (L*) did not affect the ΔE*, the b* parameter did. For example, L* did not affect the ΔE* with the treatment C-wax for *A. mangium*, *S. macrophylla*, *T. grandis* and *T. Amazonia*, whereas b* did affect it significantly.
5. The cases in which the L* parameter was the only to affect ΔE*, were mostly in AW (22 out of 25). *A. magnium* did not present such situation.
6. The treatments in which a* and b* affect ΔE* significantly, while L* does not affect it, are: *A. mangium* in NW in C-preservative; *B. quinata* in NW in the treatments C-untreated and C-wax and in AW in A-wax; *S. macrophylla* in the treatments A-wax, C-

wax and C-preservative in NW; *T. grandis* in all treatments in AW and the control sample; and lastly *T. amazonia* in AW in the treatments C- untreated and C- wax.

7. In *C. lusitanica* wood, regardless of the type of finish, the ΔE* was significantly affected by the changes in L*, a* and b*.
8. For NW, as expected, the ΔE* was affected a greater number of times by the change in the three color parameters (L*, a* and b*) in A finishes, for any type of surface treatment, with the exception of *A. mangium*, which was mostly affected by L* and b* together.

Table 3. Significance of ΔL*, Δa* and Δb* in color change (ΔE*), for 3 types of finishes with natural and accelerated exposure in 10 fast growing species from forest plantations.

.

Finishes	Coating	*Acacia mangium*		*Alnus acuminata*		*Bombacopsis quinata*		*Cupressus lusitanica*		*Gmelina arborea*		*Pinus caribaea*		*Swietenia macrophylla*		*Tectona grandis*		*Terminalia amazonia*		*Terminalia oblonga*	
		Nat	Ac	Nat	Ac	Nat	Ac	Nat	Ac	Nat	Ac	Nat	Ac	Nat	Ac	Nat	Ac	Nat	Ac	Nat	Ac
	Control	L b	L b	L a b	L a b	La b	L a b	L a b	L a b	L b	L a b	L a b	La b	L a b	L a b	L	a b	L a b	L a b	L a b	L a b
A	Untreated	L b	L b	L a b	L a b	L a b	L	L a b	L a b	L b	L b	L a b	La b	L b	L b	L a b	L a	L a b	L b	L a b	L
	Wax	L b	L b	L a b	L	L b	a b	L a b	L b	L a b	L a	L a b	L a b	a b	L b	b	-	L b	L b	L a b	L a b
	Preservative	L a b	L a b	L a b	L a	L a b	L	L b	L a b	L a b	L b	L a b	L b	L a b	L a b	b	-	L a b	L b	L a b	L a b
	Wax+preservative	L b	L b	L a b	b	L b	L a b	L a b	L a b	L a b	L	L b	L	L a b	-	a b	L	L b	-	L b	L b
B	Untreated	L b	L b	L a b	L a b	L b	L b	L a b	L a	L	L b	L a b	L b	L a b	L	L b	-	L b	L b	L b	b
	Wax	L a b	-	L b	L a b	L a b	b	L a b	L a b	L	L b	L a b	L	L a b	L	L a b	L	L a b	L	L b	L
	Preservative	L b	-	L b	L	-	L b	L b	L a b	L a b	L b	L	L	L a b	L b	L	-	L b	L b	L a b	L a b
	Oil+preservative	L a b	L a	L a b	L b	L a b	L	L a b	L	L a b	b	L b	b	L a b	L b	L a b	-	L b	-	L b	a b
C	Untreated	L a b	L b	L a b	L a b	a b	b	L b	L a b	L b	L a b	L b	L b	L a b	L b	L b	L b	L b	L	L b	a b
	Eax	b	L b	L b	L a b	a b	L a b	L a b	L a b	L b	-	L a b	L a b	a b	b	L b	b	L b	b	L b	L a b
	Preservative	a b	-	L a b	L b	L b	-	L a b	L a b	L b	-	L b	L a b	a b	L b	L b	b	L a b	L	b	L a b
	Wax+preservative	-	-	L a b	-	L b	L b	L b	L a b	L a b	L	L a b	L a b	L a b	b	L b	L a b	L b	-	L b	-

Notes: Light screening are treatments in which only L is affected, the darker screening, treatments in which only b* is affected and lined screening, treatments that only affect the parameters a* and b*.

C. Quality of the surface

According to the surface evaluation, stains on the finish appeared in few species and in few treatments. The stains were observed in *A. mangium* and *T. oblonga*, in finishes B and C in all surface treatments in AW. This flaw also appeared in *P. caribaea* in the C finish with the treatments C- wax and C- preservative. Concerning fungi on the finished surface, it was not observed in the samples of the different species or finishes exposed to AW. In NW, fungi appeared in almost all the species, except for *A. mangium*, with the treatments B-untreated and B-preservative.

In NW, fungi were not observed in *P. caribaea* in treatments B-untreated and B-preservative nor in *T. grandis* and *T. oblonga* (Table 4). Meanwhile, fungi development was an obstacle for the adequate evaluation of the sample deterioration in species with white tonalities, such as *A. acuminata*, *B. quinata*, *G. arborea*, *P. caribaea* and *T. oblonga*. Lastly, bubbles were only observed in samples exposed to AW (Table 4), and they were not observed in 2 of the 10 species studied (*B. quinata* and *G. arborea*), nor were they found in the samples of all species with finish type A, or in *A. acuminata* and *T. oblonga* with finish B. For most treatments where bubbles were found, they were observed in 100% of the samples (Table 4).

The evaluation of the surface degradation showed that after exposure none of the species with any type of finish or coating presented the irregular type of flaw or mosaic flaw. Next, the Surface Quality Index (SQI), in which irregular flaw, long and short line and switch flaw were evaluated together, showed, as expected, low values in the samples exposed to NW for most of the species, with the exception of *B. quinata*, *G. arborea*, *P. caribaea* and *T. oblonga* with finishes B and C (Figures 4c, 4e-f and 4h), for which the SQI was higher for NW than for AW.

The lowest SQI was found in the different types of finishes of all the species in NW and with finish B in *A. acuminata* in NW (Figure 4a). For *A. acuminata*, *B. quinata*, *G. arborea*, *P. caribaea* and *T. oblonga*, finish A presented lower values than finishes B and C in the different surface treatments (Figures 4b-c, 4e-f, 4j). *C. lusitanica*, *S. macrophylla*, *T. grandis* and *T. amazonia*, did not show a clear trend in the SQI behavior of the finishes, which was high for some finishes and low for others. The AW analysis found the lowest index in finish A in *C. lusitanica*, *T. amazonia* and *T. oblonga* (Figures 4d, 4i-j), while the highest IQ value was found in *B. quinata*, *G. arborea* and *P. caribaea* in finish A (Figure 4c). For *A. mangium* the highest IQ were found in surfaces treated with preservative in any of the finishes (Figure 4a). In *A. acuminata* again the surfaces treated with preservative and preservative-wax in the three types of finishes used, presented the highest IQ. Finish B in *S. macrophylla* and *T. grandis* presented the highest IQ values (Figure 4g-h).

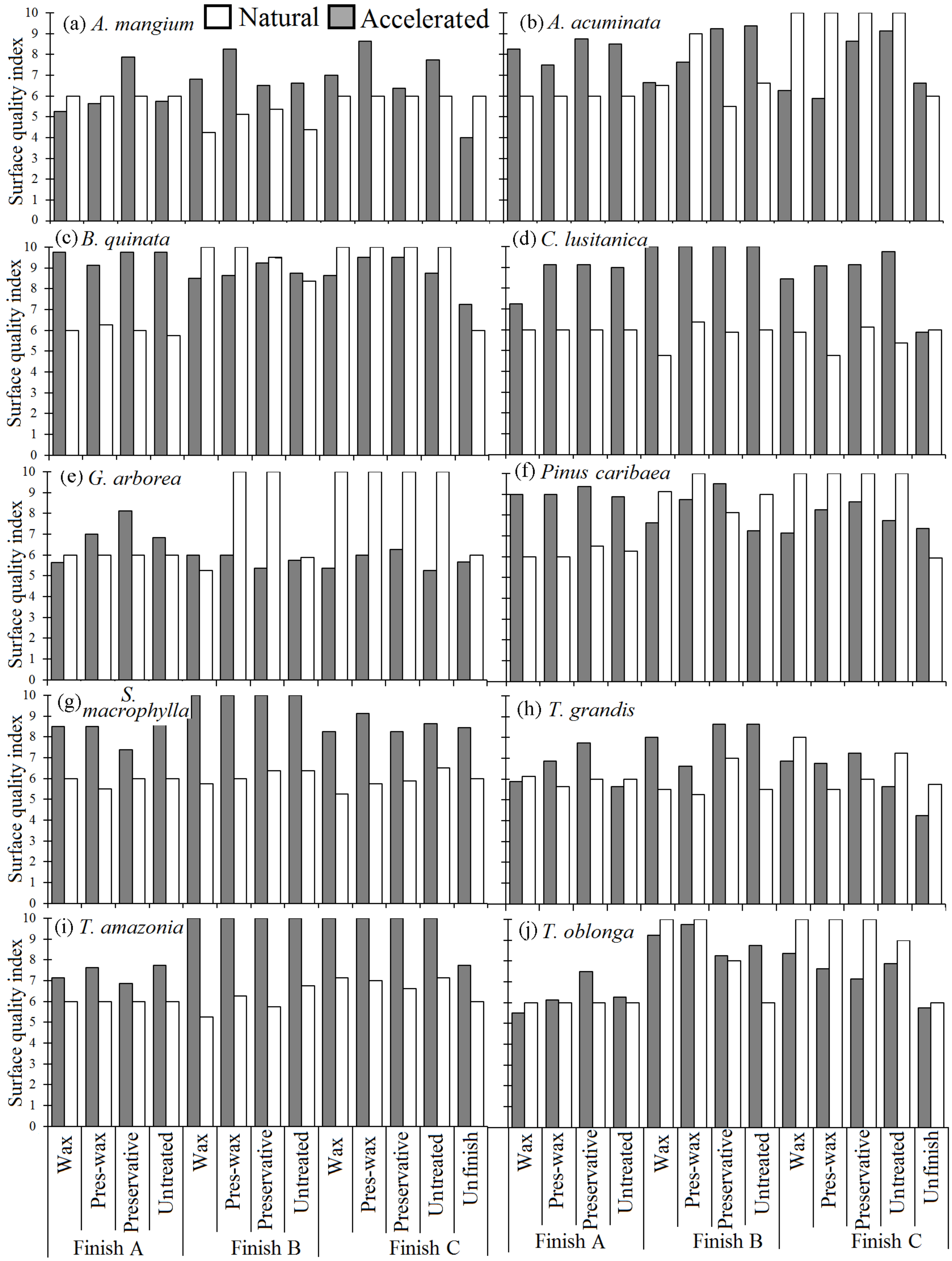

Figure 4. Surface quality index of 10 tropical plantation species exposed to natural weathering and to accelerated weathering with 3 types of finish and various treatments.

Table 4. Percentage of pieces with fungi in natural exposure, and with bubbles in accelerated exposure obtained for 10 tropical species from plantations, with 3 types of finish and various treatments.

Finishes	Coating	*Presence of fungi in natural exposure*										*Presence of bubbles in accelerated exposure*									
		Acacia mangium	*Alnus acuminata*	*Bombacopsis quinata*	*Cupressus lusitanica*	*Gmelina arborea*	*Pinus caribaea*	*Swietenia macrophylla*	*Tectona grandis*	*Terminalia amazonia*	*Terminalia oblonga*	*Acacia mangium*	*Alnus acuminata*	*Bombacopsis quinata*	*Cupressus lusitanica*	*Gmelina arborea*	*Pinus caribaea*	*Swietenia macrophylla*	*Tectona grandis*	*Terminalia amazonia*	*Terminalia oblonga*
	Control	100	100	100	100	100	100	100	100	100	100	-	-	-	-	-	-	-	-	-	-
A	Untreated	-	100	100	100	100	100	100	100	100	100	-	-	-	-	-	-	-	-	-	-
	Wax	-	100	100	100	100	100	100	100	100	100	-	-	-	-	-	-	-	-	-	-
	Preservative	-	100	100	100	100	100	100	100	100	100	-	-	-	-	-	-	-	-	-	-
	Wax-preservative	-	100	100	100	100	100	100	100	100	100	-	-	-	-	-	-	-	-	-	-
B	Untreated	50	100	50	100	100	-	100	100	100	100	100	-	-	100	-	25	75	100	100	-
	Wax	-	100	100	100	100	75	100	100	100	100	100	-	-	50	-	100	100	100	100	-
	Preservative	75	100	100	100	100	-	100	100	100	100	100	-	-	50	-	50	-	100	74	-
	Wax-preservative	-	100	100	100	100	100	100	100	100	100	100	-	-	25	-	50	100	100	100	-
C	Untreated	-	100	100	100	100	100	100	-	100	-	100	100	-	100	-	100	100	50	-	100
	Wax	-	100	100	75	100	100	100	-	100	-	100	100	-	100	-	100	75	50	-	100
	Preservative	-	-	100	100	100	100	-	-	100	-	100	100	-	100	-	100	100	25	-	100
	Wax-preservative	-	-	100	75	100	100	-	-	100	-	100	100	-	100	-	100	100	100	-	100

Notes: “-“ indicates that no fungi or bubbles were observed with the respective species and treatment.

Discussion

Initial color

The positive values found in the initial color of the finishes of the different woods, are produced by the combination of white (L*), red (a*) and yellow (b*) tonalities, which reflect the natural color of the wood, since these coatings and finishes are almost transparent (Table 1). The combination of whites, reds and yellows is a characteristic pattern of tropical woods.[22] Thus, this pattern confirms the results found in other studies for these species, with different coatings.[17,22]

The high color variation of tropical woods is due to the variation of the different parameters. The parameter influencing the most is luminosity (L*). According to this variation, two groups can be established: species with L*>54 and species with L*<54.[22] The previous affirmation agrees with the findings for the species studied, since two groups of color were found: a first group including *A. mangium*, *S. macrophylla* and *T. grandis*, with values of L*<54 (Figure 1a, 1g and 1h), are classified as dark color and a second group including *A. acuminata*, *B. quinata*, *C. lusitanica*, *G. arborea*, *P. caribaea*, *T. amazonia* and *T. oblonga* (Figure 1b-f, 1i-j), with values of L*>54, are classified as light color.

The variation found in the initial color parameters between the wood used in NW and AW (Figure 1), may be explained by the time it took to make the measurement. Although the samples in NW and AW were painted similarly, the color of the samples in AW were measured after several days, since during the accelerated aging test only 48 samples could be tested, leaving a time span between the painting and the measurement of the color. Regarding the samples used in NW, color measurement was taken immediately after applying the treatment to the wood surface. During the first days after the application of the finish, the interaction between the components of the finish and the ultraviolet rays (photodegradation) begins,[23] thus affecting the color parameters.[17]

The application of polyurethane finishes and waxes caused variations in the parameters (L*, a* and b*) and in ΔE^* in relation with the natural color of the wood (Figure 1 and

Table 2). The active components of each finish (resins and oils in finish A, and urethane prepolymer in the polyurethane in finishes B and C), together with the lignin stabilizing compounds, UV light absorbents and antioxidant agents,[8,9,23] react chemically with the lignin, cellulose, hemicellulose and extractives that are present in the wood;[8,9,11,23] the resulting chemical interaction between the wood and the coating, causes a change of magnitude of the L*, a* and b* parameters (Figure 1), and therefore a variation in the ΔE* (Table 2), in all of the studied species.

Similarly, the chemical composition of the different types of finish caused varying interactions with the wood,[24] and as a result in some species or surface treatment, one of the three parameters was not significantly affected, as is the case of *B. quinata* and *P. caribaea* with finishes B and C. In this case the parameter a* was not significantly affected (Figures 1m and 1p).

Although some parameters do not change in the species (Figure 1), ΔE* is in most cases higher than 12 units (Table 2), which is considered as a total change in color, for the reason that ΔE* is a function of the change of the 3 color parameters.[22]

Another important aspect regarding the values of ΔE* is that these were different for the species. However, the treatments applied with finish A presented the lowest values (Table 2), followed by C and B. Such result was expected since finish A presents a cedar tonality, while for finishes B and C the formulation was 100% transparent (Table 1). Due to this composition, the application of finish A tends to produce a darker color than the one produced by finishes B and C, which cause higher values of ΔE* (higher color change) in woods with high values of L* or light color woods (*A. acuminata*, *B. quinata*, *C. lusitanica*, *G. arborea*, *P. caribaea*, *T. amazonia* and *T. oblonga*). Nevertheless, the woods with the lowest values of L*, called dark woods (*A. mangium*, *S. macrophylla* and *T. grandis*), present a lower ΔE*.

Color change after exposure

Regarding the variation of Δ*E** between NW and AW after exposure, the highest values were obtained in NW. In fact, ΔE* showed values above 12 in all cases, regardless of the species or finish (Figure 2), which means a complete change of color. This variation between the two weathering conditions is due to the fact that with NW there is constant variability of solar radiation, humidity, rainfall, pollution and biotic agents, which accelerate the color degradation process, while with AW those conditions are controlled.[7,13,23-25] In this regard, Cremmers *et al.*[27] point out the difficulty of reproducing the natural environmental conditions in an accelerated test inside a chamber. Because of this adverse condition of the NW, the ΔE* is over 12 (Figure 2), and the change of color becomes a total color change of the wood.[20]

The change of color of the finishes after the exposure, in both NW and AW (Figure 2), may be explained by the processes of photodegradation of the finish in outdoor conditions.[7,23] Even if the wood is protected, these weather conditions influence the wood surface. Firstly, the degradation of lignin in the wood begins, due to UV light absorption through the finish,[23,27] causing the decomposition of the methoxyl groups and the formation of carbonyl groups and carboxyl chromoformic,[7,23] as well as the degradation of extractives by the UV light.[26] The loss of the wood lignin and extractives produces a grayish coloration, thus leading to a reduction of L*. The previous result was confirmed for all species and types of finishing, since the L* parameter affected the ΔE* value significantly (Table 3).

Lastly, the variations of Δ*E** in the different species (Figure 2) are due to the variations in the chemical compounds, mainly the extractives present in each wood type,[30] and its capacity of interaction with the finish.[14,15,26] The interaction species-finish in *A. mangium* and *T. grandis* (classified as dark color woods) was probably better in NW, showing lower values of ΔE* (Figure 2a and 2h). On the contrary, *A. acuminata*, *C. lusitanica*, *G. arborea*, *Pinus caribaea*, *T. amazonia* and *T. oblonga*, with values of L* above 54, and listed as light color woods, presented less interaction wood-finish, which resulted in higher variations of Δ*E** (Figure 2b, 2d-g, 2i and 2j). However, the high values of Δ*E** in *B. quinata*, with light color, and the lower values of Δ*E** in *S. macrophylla*, with dark color (Figure 2c and 2g), do not show the same behavior of the rest of the species, that is to say, high values of color change Δ*E** in light color and low values of Δ*E** in dark color. Such results indicate that the effects of the extractives on these species are different from the effect on other species. For example, the acetylation - which may vary between species- of

OH groups, is a strategy used in the chemical formulation of finishes to stop photodegradation.[23]

On the other hand, the trend of the condition of exposure was not defined, with light color woods producing high values of Δ*E**, and dark color woods low values of Δ*E**. In both types of exposures some light color species, such as *A. acuminata*, *B. quinata* and *G. melina*, presented high values of ΔE* (Figure 2a-c and 2e). Such results indicate that the performance of the finish in an accelerated condition does not totally reflect the result obtained with NW.

The comparison of the color change (Δ*E**) between the different finishes and coatings with the control sample, showed that most significant statistics appear with the condition AW (Figure 2), except for *A. mangium*, *B. quinata* and *G. arborea* (Figures 2a, 2c and 2e), in relation with NW. The condition AW produces less color change in the wood finish or coating than NW. In NW, however, when the differences were statistically significant, the color change was higher for some species and lower for others, without showing consistency between the type of finish and the coating used, thus indicating that – as regards to interaction with the finish or coating- each species presents its own condition in NW. However, for different species or types of finish or coating where statistical differences were found, or the Δ*E** value is higher than for wood without treatment, this result disagrees with other studies,[17,27] which show that color change is lower when some type of finish is applied. Although the purpose of the finish is to protect the natural wood color,[29] such protection becomes less effective with time, due to the loss in effectiveness of the lignin stabilizers and the UV filters of the finishes,[23] therefore the loss of the color. Based on the above, after 500 days exposure to NW, the finish had probably lost its effectiveness to maintain the color, thus indicating that fewer days may be better to test the effectiveness in tropical conditions. For example, with the 350 days exposure study carried out for *T. grandis* and *A. mangium*, both of them species used in this work, it was possible to measure the effectiveness of the finish.[17]

The analysis of the influence of the color parameters on color change (ΔE*) showed that L*, a* and b* have a significant effect on wood that has not been applied some type of finish or coating; when some type of finish or coating has been applied, L* and b* influence the most on ΔE* (Table 3). Such behavior is caused by a chemical modification of the surface due to exposure.[23,30] The UV rays that enter directly, or are let in by the wood surface coating, produce the decomposition of the lignin methoxyl groups and begin to form carbonyl and carboxyl chromoformic groups, added to the degradation of extractives.[7,23] Because of the loss of lignin and wood extractives, the wood starts to become grayish, thus increasing the value of parameter L* mainly,[7,31] which is negatively correlated with a*,[32] therefore indirectly affecting the value of ΔE* also. In addition, although the finishes are made with UV light stabilizers and antioxidants to increase resistance to weathering,[9] maintaining the color is impossible,[32] the parameters of luminosity (L*) and the yellows (b*) being the most affected. As regards to the reddish parameter (a*), it is generally related to the addition of additives to produce darker colors,[33] which is not the case, since the finishes used in the present study are transparent (Table 1), so it was expected that this parameter would be unaffected (Table 3).

Concerning AW, where parameters L*, a* and b* had no effect on ΔE*, the degradation produced by the UV radiation on the chemical components of the wood is probably not as complete as to achieve a significant influence of the 3 parameters in this type of exposure.

Quality of the surface

One of the limitations of the AW is that due to the temperature and high UV intensity, the development of stains and fungi is impeded,[28] whereas with NW, the temperature and relative humidity of tropical conditions help their development,[17,34,35] which explains why in NW fungi and stains were observed in most species and treatments (Table 4). Bubbles, on the other hand, were only observed in AW in the polyurethane finishes (Table 4). This defect is due to the application of high temperature cycles and water vapor condensation in AW, which slowly break the surface tension of the finish, causing bubbles to form.[33]

In relation with the quality of the finish surface, the absence of irregular and mosaic type flaws, coincides with the results found for other tropical species studied in Costa Rica.[17] Such defects usually appear when the finish has been exposed for long periods of time and presents poor adherence to the substrate.[35]

Exposure to UV light, to variations of temperature and relative humidity, together with exposure to water, generate degradation and erosion processes in the wood which cause defects (long and short line and switch flaw) on the finish surface, thus reducing the quality of the wood.[35,36] However, despite this degradation of the finishes, the SQI presented was higher than for wood without treatment of the surface (Figure 4), which is explained by the fact that the finish stops the degradation of lignin[7] and the loss of extractives and cellulose[27] in the wood surface, if it is not adequately protected.[35]

The high SQI obtained with polyurethane finishes (B and C) in natural weathering is due to the hard resistant film this type of finish forms and its good interaction with the wood, whereas with the oil type finish A, probably of low resistance to surface tension and response to environment, the formation of flaws and cracks (splits) on the finish is propitiated, which is reflected in the SQI.[36,37]

The low SQI found in NW was to be expected since, as commented above, the conditions of radiation, temperature, water and variations of those for long periods of time, causes the wood surface tension to rise with the additional degradation of the finish.[14,38] The entrance of biotic factors in NW (Table 4) also accelerates the deterioration processes.[35,36] However, the SQI found in *A. acuminata*, *B. quinata*, *G. arborea*, *P. caribaea* and *T. oblonga*, with finishes B and C (Figure 4c, 4e-f and 4h), was higher in NW than in AW. This result however, must be taken carefully since the defects evaluated could not be adequately observed in these species at the end of the 400 hours exposure. Irregular flaws, long and short line and switch flaws are difficult to evaluate in the mentioned species in such conditions, due to their light color.

Conclusions

The initial color of the wood from plantation species was different in each species. The L* parameter varied from 35 to 70, the a* parameter from 9 to 24 and the b* parameter from 15 to 50. The lowest values of the L* parameter, under 54, were observed in *A. mangium*, *S. macrophylla* and *T. grandis*. Those species were classified as dark color woods. Species with higher values of L*, above 54, were catalogued as light color woods. In relation to the a* parameter, the lowest values are those of *G. arborea*, *P. caribaea* and the two *Terminalia* species; *S. macrophylla* presents the highest values. Lastly, the b* parameter shows no difference between the species. The finishes changed the values of the color parameters, L* decreased and a* and b* increased for all species. Because of these changes in the parameters, the change of color was catalogued as total change. The greatest change though, was found in the wax finish, because of its cedar pigmentation.

Natural exposure was observed to produce the greatest color changes, compared to accelerated exposure. In fact, in all cases in natural exposure, the ΔE* (color change indicator) values were above 12, regardless of the species or finish applied. However, according to the observations, a 500 days natural exposure results less effective for evaluation of the finishes than 400 hours of accelerated exposure. In the analysis of the influence of the color parameters (L*, a* and b*), the color change (ΔE*) showed that L*, a* and b* significantly affect the wood to which no finish or coating has been applied, while if finish or coating has been applied, L* and b* are the main parameters affecting ΔE*.

Regarding the evaluation of defects, the stains on the finishes were present in only a few species (*A. mangium*, *P. caribaea* and *T. oblonga*) and few treatments. No fungi were observed on the finished surface in the different species, or finishes exposed to accelerated exposure, whereas in natural exposure fungi were observed in almost the totality of the species, except for *A. mangium*. Bubbles were not observed in natural exposure in any of the finishes, except for polyurethane type finishes. No bubbles were found with wax finishes. None of the species with any type of finish or surface treatment presented the irregular or mosaic flaw after natural exposure. Regarding the evaluation of the Surface Quality Index (SQI), in which flaw, long and short line and switch flaw were evaluated together, showed, as expected, low values of SQI for the natural exposure samples, except for *B. quinata*, *G. arborea*, *P. caribaea* and *T. oblonga* with finishes B and C, in which cases the value of SQI was higher in NW compared to AW, the reason being that such defects are not as visible in those species as in dark color species.

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