

Article

Modelling the Material Resistance of Wood—Part 3: Relative Resistance in above- and in-Ground Situations—Results of a Global Survey

Christian Brischke ^{1,*}, Gry Alfredsen ², Miha Humar ³, Elena Conti ⁴, Laurie Cookson ⁵, Lukas Emmerich ¹, Per Otto Flæte ⁶, Stefania Fortino ⁷, Lesley Francis ⁸, Ulrich Hundhausen ⁶, Ilze Irbe ⁹, Kordula Jacobs ¹⁰, Morten Klamer ¹¹, Davor Kržišnik ³, Boštjan Lesar ³, Eckhard Melcher ¹², Linda Meyer-Veltrup ¹³, Jeffrey J. Morrell ¹⁴, Jack Norton ⁸, Sabrina Palanti ¹⁵, Gerald Presley ¹⁶, Ladislav Reinprecht ¹⁷, Tripti Singh ¹⁸, Rod Stirling ¹⁹, Martti Venäläinen ²⁰, Mats Westin ²¹, Andrew H. H. Wong ²² and Ed Suttie ²³



Citation: Brischke, C.; Alfredsen, G.; Humar, M.; Conti, E.; Cookson, L.; Emmerich, L.; Flæte, P.O.; Fortino, S.; Francis, L.; Hundhausen, U.; et al. Modelling the Material Resistance of Wood—Part 3: Relative Resistance in above- and in-Ground Situations—Results of a Global Survey. *Forests* **2021**, *12*, 590. <https://doi.org/10.3390/f12050590>

Academic Editor: Angela Lo Monaco

Received: 29 March 2021

Accepted: 27 April 2021

Published: 8 May 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

- ¹ Wood Biology and Wood Products, University of Goettingen, 37077 Goettingen, Germany; lukas.emmerich@uni-goettingen.de
 - ² Norwegian Institute of Bioeconomy Research (NIBIO), Division of Forests and Forest Resources, Wood Technology, 1431 Ås, Norway; Gry.Alfredsen@nibio.no
 - ³ Department of Wood Science and Technology, Biotechnical Faculty, University of Ljubljana, 1000 Ljubljana, Slovenia; Miha.Humar@bf.uni-lj.si (M.H.); Davor.Krzišnik@bf.uni-lj.si (D.K.); Bostjan.Lesar@bf.uni-lj.si (B.L.)
 - ⁴ CATAS, 33048 San Giovanni al Natisone, Italy; conti@catas.com
 - ⁵ LJ Cookson Consulting, Warrandyte, VIC 3113, Australia; laurie@ljcookson.com
 - ⁶ Norwegian Institute of Wood Technology (NTI), 0314 Oslo, Norway; per.otto.flate@treeteknisk.no (P.O.F.); ulrich.hundhausen@treeteknisk.no (U.H.)
 - ⁷ VTT Technical Research Centre of Finland, 02044 Espoo, Finland; stefania.fortino@vtt.fi
 - ⁸ Department of Agriculture and Fisheries, Forestry Science, Ecosciences Precinct, Brisbane, QLD 4102, Australia; Lesley.Francis@daf.qld.gov.au (L.F.); jak.norton@gmail.com (J.N.)
 - ⁹ Latvian State Institute of Wood Chemistry, 1006 Riga, Latvia; ilzeirbe@edi.lv
 - ¹⁰ Institut für Holztechnologie Dresden (IHD), 01217 Dresden, Germany; Kordula.Jacobs@ihd-dresden.de
 - ¹¹ Danish Technological Institute (DTI), 2630 Taastrup, Denmark; mkl@teknologisk.dk
 - ¹² Thuenen Institute of Wood Research, 21031 Hamburg, Germany; eckhard.melcher@thuenen.de
 - ¹³ Heinz-Piast-Institute of Craftsmen Techniques, 30167 Hannover, Germany; Meyer@hpi-hannover.de
 - ¹⁴ National Centre for Timber Durability and Design Life (USC), University of the Sunshine Coast, Brisbane, QLD 4102, Australia; jmorrell@usc.edu.au
 - ¹⁵ CNR IBE, Italian National Research Council, Institute of Bioeconomy, 50019 Sesto Fiorentino, Italy; sabrina.palanti@ibe.cnr.it
 - ¹⁶ Department of Wood Science and Engineering, Oregon State University, Corvallis, OR 97331, USA; gerald.presley@oregonstate.edu
 - ¹⁷ Faculty of Wood Sciences and Technology, Technical University in Zvolen, 960 01 Zvolen, Slovakia; reinprecht@tuzvo.sk
 - ¹⁸ SCION, Rotorua 3010, New Zealand; Tripti.Singh@scionresearch.com
 - ¹⁹ FP Innovations, Vancouver, BC V6T 1Z4, Canada; Rod.Stirling@fpinnovations.ca
 - ²⁰ Natural Resources Institute Finland (LUKE), 57200 Savonlinna, Finland; martti.venalainen@luke.fi
 - ²¹ Research Institute of Sweden (RISE), 50462 Borås, Sweden; mats.westin@ri.se
 - ²² Faculty of Resource Science & Technology, Universiti Malaysia Sarawak (UNIMAS), Kota Samarahan 94300, Sarawak, Malaysia; ahhwong@unimas.my
 - ²³ Building Research Establishment, Garston, Watford WD25 9XX, UK; Ed.Suttie@bregroup.com
- * Correspondence: christian.brischke@uni-goettingen.de

Abstract: Durability-based designs with timber require reliable information about the wood properties and how they affect its performance under variable exposure conditions. This study aimed at utilizing a material resistance model (Part 2 of this publication) based on a dose–response approach for predicting the relative decay rates in above-ground situations. Laboratory and field test data were, for the first time, surveyed globally and used to determine material-specific resistance dose values, which were correlated to decay rates. In addition, laboratory indicators were used to adapt the material resistance model to in-ground exposure. The relationship between decay rates in- and above-ground, the predictive power of laboratory indicators to predict such decay rates,

and a method for implementing both in a service life prediction tool, were established based on 195 hardwoods, 29 softwoods, 19 modified timbers, and 41 preservative-treated timbers.

Keywords: biological durability; dose–response model; fungal decay; moisture dynamics; moisture performance; service life prediction; water uptake and release; wetting ability

1. Introduction

Performance-based building and durability-based design with timber requires detailed information about the material properties and the environmental conditions it will be exposed to. For outdoor applications, durability against wood-deteriorating organisms of wood plays an important role, whether the material is untreated or treated with the aim of improving its durability. The relationship between exposure and the resistance of a building material is the base for structural engineering, wherein acceptance for a chosen design and material is expressed as (Equation (1)):

$$\text{Exposure} \leq \text{Resistance} \quad (1)$$

Exposure of wood can be characterized through the climatic variables at a specific location, the structural design, and how these affect the parameters that are crucial for the growth and decay activity of wood-degrading organisms such as insects and fungi. Several research projects in Australia [1] and Europe [2–4] focused on developing models and guidelines for service life prediction and performance-based design with timber in outdoor use.

The exposure can be expressed as an exposure dose (D_{Ed}) determined by daily averages of wood temperature and wood moisture content (MC). With the help of numerical and empirical models, macro climate data and information about design details can be used to quantify the exposure dose in specific detail [5]. The accuracy of the models and their predictive powers vary [6], not least because the moisture-induced dose component always interacts with the permeability to water and the wetting ability of wood [7]. The material-inherent resistance of wood against different decay organisms can be defined as a resistance dose (D_{Rd}). The dose is expressed in days (d) with optimum moisture and temperature conditions for fungal decay. According to [8], the above-mentioned design principle can be read as expressed in Equation (2):

$$D_{Ed} \leq D_{Rd} \quad [\text{d}] \quad (2)$$

where:

D_{Ed} is the exposure dose (d);

D_{Rd} is the material resistance dose (d);

In Part 1 and 2 of this publication [9,10], we focus on the counterpart of the exposure dose, which is the resistance, expressed as resistance dose, D_{Rd} . The latter is considered to be the product of a critical dose, D_{crit} , and two factors considering the wetting ability of wood (k_{wa}) and its inherent durability (k_{inh}). The approach to do this is given by the following Equation (3), according to Ref. [3]:

$$D_{Rd} = D_{crit} \cdot k_{wa} \cdot k_{inh} \quad [\text{d}] \quad (3)$$

where:

D_{Rd} is the material resistance dose (d);

D_{crit} is the critical dose (d) corresponding to decay rating 1 (EN 252 [11]);

k_{wa} is a factor accounting for the wetting ability of the material (-) relative to a reference wood species;

k_{inh} is a factor accounting for the inherent protective properties of the material against decay (-) relative to a reference wood species.

In previous approaches, Norway spruce (*Picea abies*) was defined as the reference material, which was also used to define a reference design situation, i.e., a planed horizontal board without contact faces or any other water-trapping items, which is exposed in the Swedish city of Uppsala [3]. All parameters that deviated from this reference situation were then considered by calculating a site-specific exposure dose and several modifying factors accounting for shelter, water traps, driving wind loads, etc. Similarly, the two factors k_{inh} and k_{wa} solely refer to the respective properties of Norway spruce [2–4], which limit the range of useful datasets to those including Norway spruce as one of the species being tested. In particular, in standard tests (e.g., EN 113-2 [12], AWPA E7 [13]) reference species are the sapwood of different pine species (softwoods) or beech (hardwoods). In Part 1 of this publication [9], we performed comparative durability and moisture performance tests with Norway spruce, Scots pine sapwood (*Pinus sylvestris*), and European beech (*Fagus sylvatica*), and determined factors between the three species for the resistance against different rot types and for different kinds of moisture uptake and release. The latter allows us to utilize further data for: (1) improving and validating existing material resistance models (Part 2 of this publication [10]), and (2) generating a material resistance database for different wood species and treated timbers. Data can be gathered from current and still-ongoing, as well as historic, durability tests.

The aim of this study was therefore to survey wood durability test data, utilize them for implementation in a material resistance model, and generate a database for service life prediction. Alternatively to the above-described approach, the material resistance dose (D_{Rd}) can also be obtained directly from field tests with a sufficient exposure time. Again, besides Norway spruce, other reference species, such as pine sapwood (*Pinus* spp.), can be used to calculate relative D_{Rd} values. The accessible data from above-ground field tests are sparse [14], but their overall value is high, since under field exposure conditions the complexity of climate-induced variables and material resistance is entirely captured. Finally, worldwide, a significant volume of timber is used in contact with soil, where other decay organisms dominate compared to above-ground situations. Therefore, we also aimed to quantify the exposure-specific material resistance dose for wood in-ground contact.

2. Materials and Methods

2.1. Data Capturing

Data on material resistance based upon laboratory and field wood durability tests and different wetting ability tests were gathered from scientific publications, research reports, and technical guidelines. In addition, raw data in terms of mass loss, decay ratings or moisture-related characteristics were provided by numerous researchers. Information about the materials included in this study, and the respective sources of data used to calculate the modifying factors k_{wa} and k_{inh} and the decay rates, $v_{rel.}$, are summarized in Tables 1–4. The maximum threshold (Thr) for both factors was set to 18.0, due to the best model fit obtained in Part 2 of this publication [10].

Meyer-Veltrup et al. [7] determined the modifying factors k_{inh} and k_{wa} on the basis of different laboratory durability test methods against brown, white and soft rot causing fungi, and different moisture performance tests accounting for liquid water uptake during submersion, water vapor uptake at high relative humidity (RH), desorption tests at low RH (approx. 0%), and the capillary water uptake (CWU) of end-grain surfaces. The test protocols are described in detail in Part 1 of this publication [9]. In each case the reference wood species was Norway spruce (*Picea abies*). This survey enlarged the pool of data sets and also included results where European beech (*Fagus sylvatica*), the sapwood of different pine species (e.g., *P. elliotii*, *P. ponderosa*, *P. radiata*), and white spruce (*Picea engelmannii*) were used as reference species. Factors accounting for the relationship between the material resistance and its respective components for the different reference species were applied as described in Part 1 of this publication [9]. In addition to standard basidiomycete tests with brown and white rot fungi (e.g., EN 113-2 [12]) and soil contact soft rot tests under laboratory (e.g., ENV 807 [15]) and field conditions (e.g., EN 252 [11]), results from

basidiomycete mini-block tests [16] were considered. Results from submersion and floating tests according to CEN/TS 16818 [17] and Welzbacher and Rapp [18] were considered for calculating k_{wa} factors, in addition to the tests described in Part 1 of this publication [9].

Furthermore, results from above-ground tests performed at different locations worldwide were obtained in horizontal lap-joint tests [19], sandwich tests [20], decking tests [21,22], deck tests [23,24], close-to-ground mini-stake tests [25], cross-brace tests [26], panel tests [27], flat panel tests [28], multiple layer tests [14], block tests [25,29], vertically hanging stakes [30], painted and unpainted L-joint tests [14], horizontal double layer tests [30], and modified horizontal double layer tests [31].

2.2. Data Assessment

Decay rating of specimens in- and above-ground was performed regularly (usually once per year) with the help of a pick test. The depth and distribution of decay were determined and rated using the five-step scheme according to EN 252 [11] as follows: 0 = Sound; 1 = Slight attack; 2 = Moderate attack; 3 = Severe attack; 4 = Failure. Some studies used the American and/or Australian rating system (10 to 0), which were transformed to the EN 252 scale as suggested by Stirling et al. [32].

Relative decay rates, $v_{rel.}$, were determined for in-ground and above-ground exposure. Therefore, decay rates, v , i.e., the decay rating per exposure time, were calculated for each specimen and averaged. The mean decay rate, v_{mean} , for a material under test was next compared with that of a reference species, and $v_{rel.}$ was provided relative to Norway spruce. Conversion factors [9] were used when employing other reference species than Norway spruce. A more detailed description of the process for determining decay rates can be found in Part 2 of this publication [10]. The general procedure for determining and modelling decay rates for in-ground and above-ground exposure conditions is illustrated in Figure 1.

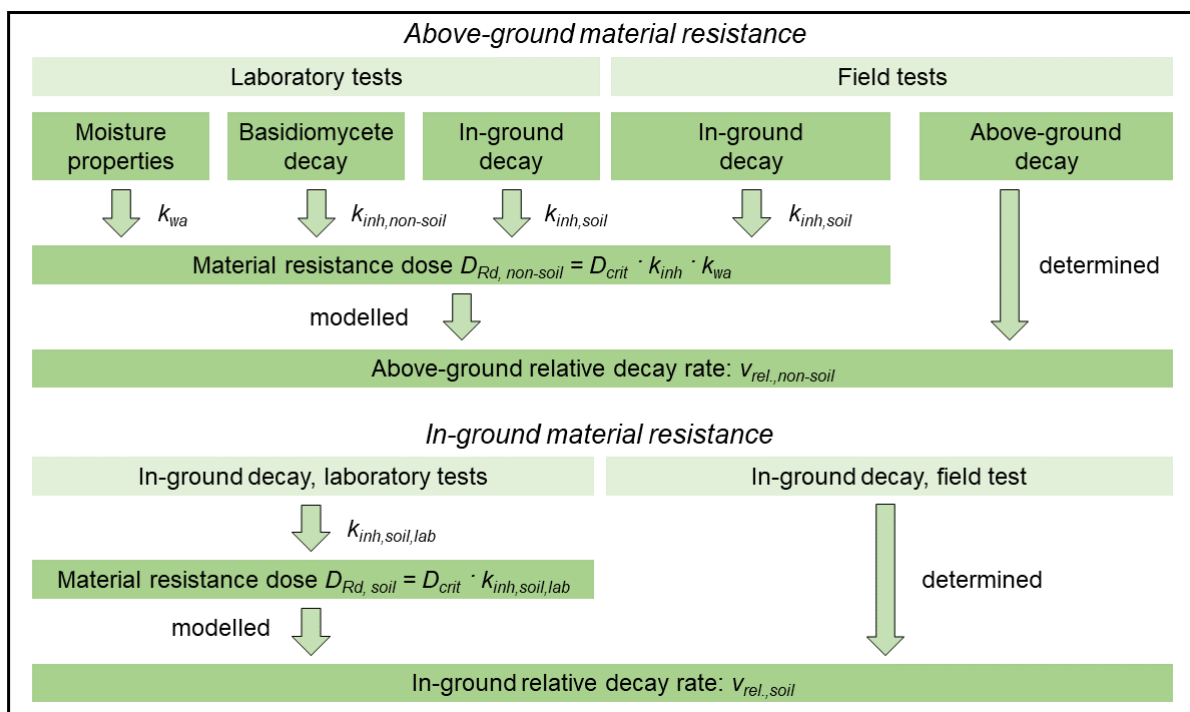


Figure 1. General procedure for determining and modelling relative decay rates, $v_{rel.}$, for in-ground and above-ground exposure conditions. A more detailed edcsription of the different steps is provided in Part 1 and 2 of this publication [9,10].

The modifying factors k_{inh} and k_{wa} were determined separately for each material and test applied. In Part 2 of this publication, the original resistance model [7] was assessed, and different calculation methods for both modifying factors were evaluated, with the aim of

improving the overall fit of the model. Accordingly, k_{wa} is the arithmetic mean of factors accounting for: (1) liquid water uptake (LWU), (2) vapor uptake (VU), (3) water release (WR), and (4) capillary water uptake (CWU). Factors accounting for the inherent protective properties of wood were calculated separately based on soil contact tests ($k_{inh,soil}$) and tests without soil contact ($k_{inh,non-soil}$). The latter is the mean of factors derived from laboratory tests with brown and white rot fungi, both decay types being weighted equally. For modelling the material resistance above-ground, k_{inh} is calculated as follows (Equation (4)):

$$k_{inh} = \frac{\frac{\sum_{i=1}^n k_{inh,soil,i}}{n} + \frac{\sum_{j=1}^n k_{inh,non-soil,j}}{n}}{2} \quad (4)$$

where:

k_{inh} is the factor accounting for the inherent protective properties of the material against decay (-);

$k_{inh,soil,i}$ is the factor accounting for the inherent protective properties of the material against decay in tests with soil contact (-);

$k_{inh,non-soil,j}$ is the factor accounting for the inherent protective properties of the material against decay in tests without soil contact (-);

n is the number of tests.

For modelling the material resistance in the ground, $k_{inh,soil}$ was used. Laboratory and field tests were used to determine $k_{inh,soil}$, and where available the mean of both was calculated. Since the k_{inh} obtained from in-ground field tests is the inverse of the decay rate in soil contact, it cannot be used to predict the latter. Hence, we distinguished $k_{inh,soil,lab}$ based on soil bed and other laboratory soft rot tests, and $k_{inh,soil,field}$, i.e., the inverse $v_{rel,soil}$. Consequently, the material resistance dose in soil contact, $D_{Rd,soil}$, was calculated as follows (Equation (5)):

$$D_{Rd,soil} = D_{crit} \cdot k_{inh,soil,lab} \text{ [d]} \quad (5)$$

where:

$D_{Rd,soil}$ is the material resistance dose in soil contact (d);

D_{crit} is the critical dose corresponding to decay rating 1 (EN 252 [11]) (d);

$k_{inh,soil,lab}$ is a factor accounting for the inherent protective properties of the material against decay in soil contact (-) relative to a reference wood species and determined in laboratory test.

Table 1. Parameters for predicting the material resistance of untreated hardwoods in- and above-ground. k_{inh} = factor accounting for protective inherent properties based on white rot, brown rot, and soil contact tests; $k_{inh,soil,lab}$ = factor accounting for protective inherent properties based on laboratory test with soil contact and soft rot fungi; k_{wa} = factor accounting for moisture performance (wetting ability); $D_{Rd,rel.}$ = relative resistance dose; $v_{rel.}$ = relative decay rate; sw = sapwood. Calculated $v_{rel.}$ in italics.

Wood Species	Common Name	Above-Ground				In-Ground			References
		k_{inh}	k_{wa}	$D_{Rd,rel.}$	$v_{rel.}$	$k_{inh,soil,lab}$	$D_{Rd,rel.}$	$v_{rel.}$	
<i>Acacia mangium</i>	Black wattle	-	-	-	0.14	-	-	-	[23]
<i>Acer platanoides/A. pseudoplatanus</i>	Norway maple/Sycamore	1.38	1.01	1.39	0.90	-	1.02	0.98	[7,33–37]
<i>Acer saccharum</i>	Sugar maple	-	-	-	1.14	-	-	-	[26]
<i>Azelia bipindensis</i>	Doussié	11.72	-	-	-	6.54	6.54	0.15	[38]
<i>Alnus glutinosa</i>	Black alder	0.89	1.06	0.94	1.35	0.33	0.72	0.90	[7,35,37,39,40]
<i>Alnus rubra</i>	Red alder sw	-	-	-	1.33	-	-	-	[26]
<i>Anacardium excelsum</i>	Espavé	-	-	-	1.32	-	0.97	1.03	[27]
<i>Andira inermis</i>	Cocú	-	-	-	0.25	-	0.97	1.03	[27]

Table 1. Cont.

Wood Species	Common Name	Above-Ground				In-Ground			References
		k_{inh}	k_{wa}	$D_{Rd,rel.}$	$v_{rel.}$	$k_{inh,soil,lab}$	$D_{Rd,rel.}$	$v_{rel.}$	
<i>Aspidosperma megalocarpon</i>	Carreto	-	-	-	0.25	-	2.91	0.34	[27]
<i>Astronium graveolens</i>	Zorro	-	-	-	0.25	-	5.11	0.20	[27]
<i>Avicennia marina</i>	Mangle salado	-	-	-	1.32	-	0.97	1.03	[27]
<i>Backhousia bancroftii</i>	Johnstone River hardwood	-	-	-	0.25	-	-	-	[14]
<i>Bagassa guianensis</i>	Tatajuba	-	-	-	0.10	-	-	-	[41]
<i>Betula alleghaniensis</i>	Yellow birch	-	-	-	1.07	-	-	-	[26]
<i>Betula pendula/B. pubescens</i>	Silver birch/Downy birch	0.93	0.90	0.84	0.95	-	0.88	1.13	[7,35,39,40]
<i>Bombacopsis quinata</i>	Cedro espino	-	-	-	0.25	-	5.11	0.20	[27]
<i>Bombacopsis sessilis</i>	Ceibo	-	-	-	1.32	-	0.97	1.03	[27]
<i>Brosium</i> sp.	Berba	-	-	-	1.32	-	0.97	1.03	[27]
<i>Brosimum utile</i>	Sande	1.30	-	-	-	1.27	1.27	0.79	[38]
<i>Bursera simaruba</i>	Almaácigo	-	-	-	1.32	-	0.97	1.03	[27]
<i>Byrsonima crassifolia</i>	Nance	-	-	-	0.44	-	2.91	0.34	[27]
<i>Caldcluvia australiensis</i>	Rose alder	-	-	-	0.50	-	-	-	[14]
<i>Calophyllum brasiliense</i>	María	8.78	-	-	0.25	-	2.91	0.34	[27]
<i>Calophyllum candidissium</i>	Lemonwood	-	-	-	0.44	-	2.91	0.34	[27]
<i>Carapa slateri</i>	Cedro macho	-	-	-	0.25	-	2.91	0.34	[27]
<i>Carapa</i> sp.	Cedro vino	-	-	-	0.25	-	2.91	0.34	[27]
<i>Cardwellia sublimis</i>	Northern silky oak	-	-	-	0.52	-	-	-	[14]
<i>Cariniana pyriformis</i>	Chibugá, albaros	-	-	-	0.25	-	2.91	0.34	[27]
<i>Caryocar costaricense</i>	Henené	-	-	-	0.13	-	6.81	0.15	[27]
<i>Caryocar</i> sp.	Ajo	-	-	-	0.25	-	2.91	0.34	[27]
<i>Cassia moschata</i>	Bronze shower	-	-	-	0.19	-	5.11	0.20	[27]
<i>Castanea sativa</i>	Sweet chestnut	7.36	1.27	9.31	0.00	3.03	2.38	0.57	[35,39,40,42–44]
<i>Cedrela odorata</i>	Cedro amargo	6.00	-	-	0.44	-	2.91	0.34	[27]
<i>Cedrela</i> sp.	Cedro granadino	-	-	-	0.44	-	0.97	1.03	[27]
<i>Cedrelinga cateniformis</i>	Cedrorana	-	-	-	0.40	-	-	-	[41]
<i>Centrolobium orinocense</i>	Amarillo de Guayaquil	-	-	-	0.19	-	5.11	0.20	[27]
<i>Chlorophora tinctoria</i>	Mora	-	-	-	0.13	-	2.91	0.34	[27]
<i>Chrysophyllum cainito</i>	Star apple	-	-	-	0.44	-	0.97	1.03	[27]
<i>Colubrina glandulosa</i>	Carbonero de amunición	-	-	-	0.13	-	6.81	0.15	[27]
<i>Concarpus erectus</i>	Zaragosa	-	-	-	0.19	-	5.11	0.20	[27]
<i>Copaifera aromatica</i>	Cabimo	-	-	-	0.19	-	5.11	0.20	[27]
<i>Cordia alliodora</i>	Laurel negro	-	-	-	0.44	-	2.91	0.34	[27]
<i>Cordia elaeagnoides</i>	Bocote	-	-	-	-	-	16.83	0.06	[27]
<i>Cornus disciflora</i>	Mata hombro	-	-	-	1.32	-	0.97	1.03	[27]
<i>Corylus avellana</i>	Common hazel	-	-	-	-	-	0.45	2.23	[-] ¹
<i>Corymbia citriodora</i>	Lemon-scented gum	-	-	-	0.14	-	-	-	[14,23,28]
<i>Corymbia maculata</i>	Spotted gum	4.40	-	-	0.26	-	2.71	0.37	[28,45,46]
<i>Coumarouna oleifera</i>	Almendro	-	-	-	0.25	-	5.11	0.20	[27]
<i>Croton panamensis</i>	Sangre	-	-	-	3.30	-	0.39	2.58	[27]
<i>Dacryodes copularis</i>	Anime	2.12	-	-	-	2.69	2.69	0.37	[38]
<i>Dacryodes copularis</i>	Anime sw	3.25	-	-	-	1.92	1.92	0.52	[38]
<i>Dalbergia granadillo</i>	Dalbergia	-	-	-	-	-	18.00	0.06	[47]
<i>Dalbergia retusa</i>	Cocobolo	-	-	-	0.06	-	10.04	0.10	[27]
<i>Diabyanthera gordonaefolia</i>	Cuangare	1.20	-	-	-	0.74	0.74	0.36	[38]
<i>Dialium guianense</i>	Tamarindo	-	-	-	0.44	-	0.97	1.03	[27]
<i>Dialyanthera otoba</i>	Miguelario	-	-	-	1.32	-	0.97	1.03	[27]
<i>Dicorynia guianensis</i>	Basralocus	10.51	1.27	13.39	0.19	-	5.11	0.20	[27,35,37,48,49]
<i>Diphysa robinoides</i>	Macano	-	-	-	0.13	-	6.81	0.15	[27]
<i>Dipterocarpus</i> spp.	Keruing	7.54	-	-	0.19	-	11.18	0.09	[23,50,51]
<i>Distemonanthus benthamianus</i>	Movingui	9.81	-	-	-	10.84	10.84	0.09	[35,38]
<i>Dryobalanops</i> spp.	Kapur	9.18	-	-	0.14	-	4.96	0.20	[14,51,52]
<i>Entandrophragma cylindricum</i>	Sapelli	-	-	-	0.56	-	-	-	[41]
<i>Enterolobium cyclocarpum</i>	Monkey-ear tree	-	-	-	0.25	-	3.14	0.32	[27]
<i>Erythrina glauca</i>	Gallito	-	-	-	3.30	-	0.39	2.58	[27]

Table 1. Cont.

Wood Species	Common Name	Above-Ground				In-Ground			References
		k_{inh}	k_{wa}	$D_{Rd,rel.}$	$v_{rel.}$	$k_{inh,soil,lab}$	$D_{Rd,rel.}$	$v_{rel.}$	
<i>Eschweilera</i> sp.	Guayabo macho	-	-	-	0.25	-	5.11	0.20	[27]
<i>Eucalyptus astringens</i>	Brown mallet	-	-	-	0.28	-	-	-	[28]
<i>Eucalyptus camaldulensis</i>	River red gum	-	-	-	0.03	-	-	-	[28]
<i>Eucalyptus cladocalyx</i>	Sugar gum	-	-	-	0.13	-	-	-	[28]
<i>Eucalyptus deglupta</i>	Kamamere	-	-	-	0.48	-	-	-	[14]
<i>Eucalyptus delegatensis</i>	Alpine ash	-	-	-	0.49	-	-	-	[14]
<i>Eucalyptus drepanophylla</i>	Ironbark	-	-	-	0.16	-	-	-	[14]
<i>Eucalyptus grandis</i>	Rose gum	-	-	-	0.18	-	-	-	[14]
<i>Eucalyptus leucoxylon</i>	Yellow gum	-	-	-	0.19	-	-	-	[28]
<i>Eucalyptus obliqua</i>	Messmate	-	-	-	0.37	-	-	-	[14,28]
<i>Eucalyptus occidentalis</i>	Swamp yate	-	-	-	0.32	-	-	-	[28]
<i>Eucalyptus pilularis</i>	Black butt	-	-	-	0.16	-	-	-	[14]
<i>Eucalyptus regnans</i>	Mountain ash	-	-	-	0.65	-	0.39	2.56	[14,28]
<i>Eucalyptus resinifera</i>	Red mahogany	-	-	-	0.11	-	-	-	[14]
<i>Eucalyptus saligna</i>	Sydney blue gum	-	-	-	0.19	-	-	-	[14]
<i>Eucalyptus sideroxylon</i> / <i>E. tricarpa</i>	Red ironbark	-	-	-	0.15	-	-	-	[28]
<i>Fagus sylvatica</i>	European beech	0.79	1.15	0.91	1.17	0.40	0.61	1.43	[7,14,22,34–41,44,49,53–59]
<i>Flindersia brayleyana</i>	Queensland maple	-	-	-	0.51	-	-	-	[14]
<i>Fraxinus excelsior</i>	European ash	2.50	1.00	2.50	0.39	0.44	1.30	0.71	[7,22,35,39,40]
<i>Genipa americana</i>	Jagua	-	-	-	1.32	-	0.97	1.03	[27]
<i>Gleditsia triacanthos</i>	Honey locust	5.71	1.64	9.35	0.11	-	1.96	0.51	[-] ¹
<i>Gliricida sepium</i>	Bala	-	-	-	0.13	-	6.81	0.15	[27]
<i>Guajacum officinale</i>	Pockwood	-	-	-	0.06	-	10.22	0.10	[27]
<i>Guarea longipetiola</i>	Chuchupate	-	-	-	0.44	-	2.91	0.34	[27]
<i>Guarea guara</i>	Guaragao	-	-	-	0.19	-	6.81	0.15	[27]
<i>Heritiera utilis</i>	Niangon	-	-	-	-	2.44	2.44	0.41	[38]
<i>Hieronima alchorneoides</i>	Pantano	-	-	-	0.44	-	0.97	1.03	[27]
<i>Hippomane mancinella</i>	Manzanillo	-	-	-	3.30	-	0.39	2.58	[27]
<i>Humiriastrume procerum</i>	Chanul	5.36	-	-	-	3.02	3.02	0.33	[38]
<i>Hura crepitans</i>	Nuno	-	-	-	3.30	-	0.39	2.58	[27]
<i>Hura polyandra</i>	Possum wood	-	-	-	-	-	3.06	0.33	[47]
<i>Hyeronima alchorneoides</i>	Zapatero	7.16	-	-	-	1.94	1.94	0.52	[-] ¹
<i>Hymenaea courbaril</i>	Algarrobo	-	-	-	0.25	-	5.11	0.20	[27]
<i>Icuria dunensis</i>	Ncurri	4.77	-	-	-	3.96	3.96	0.25	[60]
<i>Intsia bijuga</i>	Merbau	14.69	2.13	31.33	0.25	-	16.33	0.06	[7,35,46,61]
<i>Koompassia malaccensis</i>	Menggris	8.70	-	-	0.32	12.06	12.06	0.08	[23,50,51]
<i>Lafoënsia puniceifolia</i>	Amarillo negro	-	-	-	0.25	-	2.91	0.34	[27]
<i>Laguncularia racemosa</i>	Mangle blanco	-	-	-	0.25	-	0.97	1.03	[27]
<i>Lecythis ampla</i>	Coco	-	-	-	0.19	-	6.81	0.15	[27]
<i>Lecythis</i> spp.	Coco	-	-	-	0.25	-	2.91	0.34	[27]
<i>Licania arborea</i>	Raspa	-	-	-	1.32	-	0.97	1.03	[27]
<i>Licania pittieri</i>	Jigua negra	-	-	-	0.44	-	2.91	0.34	[27]
<i>Liquidambar styraciflua</i>	Sweetgum sw	-	-	-	1.78	-	-	-	[26]
<i>Lonchocarpus</i> sp.	Iguanillo	-	-	-	0.33	-	2.91	0.34	[27]
<i>Lophira alata</i>	Bongossi	12.23	1.41	17.23	0.19	-	10.52	0.20	[27,35,37,38,48,49,62,63]
<i>Lophostemon confertus</i>	Brush box	-	-	-	0.26	-	-	-	[14]
<i>Luehea seemannii</i>	Guácimo	-	-	-	1.32	-	0.97	1.03	[27]
<i>Magnolia sororum</i>	Vaco	-	-	-	0.25	-	2.91	0.34	[27]
<i>Manilkara bidentata</i>	Massaranduba	12.41	-	-	0.19	-	6.81	0.15	[27]
<i>Manilkara chicle</i>	Níspero zapote	-	-	-	0.19	-	2.91	0.34	[27]
<i>Manilkara</i> sp.	Rasca	-	-	-	0.44	-	2.91	0.34	[27]
<i>Micropholis</i> spp.	Curupixa	3.07	-	-	-	1.11	1.11	0.90	[38]
<i>Milicia excelsa</i>	Iroko	12.07	-	-	-	18.00	11.81	0.18	[38,52]
<i>Millettia laurentii</i>	Wenge	13.86	-	-	-	13.92	13.92	0.07	[38]
<i>Minquartia guianensis</i>	Manwood	-	-	-	0.13	-	6.81	0.15	[27]
<i>Mora excelsa</i>	Black Mora	4.89	-	-	-	-	2.35	0.46	[52]
<i>Mora oleifera</i>	Alcornoque	-	-	-	0.44	-	2.91	0.34	[27]
<i>Myroxylon balsamum</i>	Bálsamo	-	-	-	0.19	-	5.11	0.20	[27]
<i>Nectandra</i> spp.	Jigua baboso	3.51	-	-	-	1.28	1.28	0.78	[38]
<i>Nectandra</i> spp.	Jigua baboso sw	2.23	-	-	-	0.93	0.93	1.08	[38]
<i>Nectandra whitei</i>	Bambito	-	-	-	0.25	-	2.91	0.34	[27]
<i>Neolamarckia cadamba</i>	Kelampayan	-	-	-	1.46	-	-	-	[23]
<i>Neorites kevedianus</i>	Fishtail silky oak	-	-	-	0.18	-	-	-	[14]

Table 1. Cont.

Wood Species	Common Name	Above-Ground				In-Ground			References
		k_{inh}	k_{wa}	$D_{Rd,rel.}$	$v_{rel.}$	$k_{inh,soil,lab}$	$D_{Rd,rel.}$	$v_{rel.}$	
<i>Ocotea</i> spp.	Aguacatillo	10.00	-	-	-	11.93	11.93	0.08	[38]
<i>Ocotea</i> spp.	Aguacatillo sw	9.42	-	-	-	11.67	11.67	0.09	[38]
<i>Ocotea dendrodaphne</i>	Ensiva	-	-	-	0.19	-	6.81	0.15	[27]
<i>Ocotea rodiei</i>	Greenheart	-	-	-	0.06	-	10.22	0.10	[27]
<i>Paramachaerium gruberi</i>	Sangrillo negro	-	-	-	0.25	-	5.11	0.20	[27]
<i>Parashorea tomentella</i>	White Lauan	-	-	-	-	0.93	2.14	0.47	[52]
<i>Paulownia</i> spp.	Kiri	4.92	0.98	4.82	0.21	-	0.51	1.95	[37], [-] ¹
<i>Pelliciera rhizophorae</i>	Palo de sal	-	-	-	1.32	-	0.97	1.03	[27]
<i>Peltogyne</i> spp.	Amaranth	11.17	1.82	20.33	0.25	-	5.11	0.20	[27,33,37]
<i>Peniactlethra macroloba</i>	Gavilán	-	-	-	0.25	-	2.91	0.34	[27]
<i>Pericopsis angolensis</i>	Muanga	12.54	-	-	-	7.07	7.07	0.14	[60]
<i>Persea rigens</i>	Amarillo	10.96	-	-	-	11.50	11.50	0.09	[38]
<i>Persea rigens</i> sw	Amarillo sw	8.47	-	-	-	5.45	5.45	0.18	[38]
<i>Phoebe johonstonii</i>	Aguacatillo	-	-	-	1.32	-	0.39	2.58	[27]
<i>Pithecellobium mangense</i>	Uña de gato	-	-	-	0.13	-	10.22	0.10	[27]
<i>Pithecellobium saman</i>	Rain tree	-	-	-	0.44	-	2.91	0.34	[27]
<i>Platymiscum pinnatum</i>	Quirá	-	-	-	0.19	-	6.81	0.15	[27]
<i>Populus balsamifera</i>	Balsam poplar sw	-	-	-	1.00	-	-	-	[26]
<i>Populus nigra/Populus</i> spp.	Poplar	0.85	1.04	0.88	1.14	0.56	0.76	1.04	[35,37,38,49,52,58]
<i>Populus tremula</i>	Aspen	1.03	0.95	0.97	1.04	0.25	0.94	0.62	[7,14,34,36,39,40]
<i>Pouteria campechiana</i>	Mamecillo	-	-	-	0.44	-	2.91	0.34	[27]
<i>Pouteria chiricana</i>	Nispero de monte	-	-	-	0.44	-	0.97	1.03	[27]
<i>Prioria copaifera</i>	Cativo	-	-	-	3.30	-	0.39	2.58	[27]
<i>Prunus avium</i>	Cherry	-	0.81	-	0.70	-	-	-	[7]
<i>Prunus serotina</i>	Black cherry	2.73	0.84	2.28	0.44	1.69	1.69	0.59	[64]
<i>Pseudolachnostylis maprounaefolia</i>	Ntholo	13.50	-	-	-	9.00	9.00	0.11	[60]
<i>Quercus robur /Q. petraea</i>	European oak	7.05	1.41	9.92	0.47	1.94	2.77	0.38	[7,14,18,21,22,27,30,33,35,37–40,49,50,52,53,55,57,59,62,63,65]
<i>Rhizophora brevistyla</i>	Mangle rojo (Pacific)	-	-	-	0.44	-	2.91	0.34	[27]
<i>Rhizophora mangle</i>	Mangle rojo (Atlantic)	-	-	-	0.44	-	0.97	1.03	[27]
<i>Robinia pseudoacacia</i>	Black locust	7.47	1.93	14.39	0.24	1.38	2.67	0.19	[7,30,35,37,39,40,49,59,62,63,66]
<i>Salix caprea</i>	Goat willow	1.36	0.99	1.35	0.50	-	1.46	0.69	[7], [-] ¹
<i>Shorea</i> spp.	Meranti	7.30	-	-	-	12.35	7.38	0.42	[38,52]
<i>Shorea</i> spp.	Light Red Meranti	-	-	-	0.46	-	-	-	[14,23,41]
<i>Shorea</i> spp.	Dark Red Meranti	-	-	-	0.51	-	-	-	[41]
<i>Shorea</i> spp.	Red balau	-	-	-	0.12	-	-	-	[14]
<i>Shorea macrophylla</i>	Engkabang jantong	-	-	-	1.63	-	-	-	[23]
<i>Sorbus aucuparia</i>	Rowan	1.36	0.86	1.17	0.56	1.12	1.46	0.56	[7,64]
<i>Sterculia apetala</i>	Panamá	-	-	-	3.30	-	0.39	2.58	[27]
<i>Sterculia appendiculata</i>	Metil	2.33	-	-	-	0.82	0.82	1.22	[60]
<i>Swaetzia panamensis</i>	Cutarro	-	-	-	0.19	-	5.11	0.20	[27]
<i>Swaetzia simplex</i>	Cutarro	-	-	-	0.19	-	0.97	1.03	[27]
<i>Sweetia panamensis</i>	Malvecino	-	-	-	0.25	-	2.91	0.34	[27]
<i>Swietenia humillis</i>	Mexican mahogany	-	-	-	0.19	-	11.22	0.09	[27]
<i>Swietenia macrophylla</i>	Mahogany	-	-	-	0.44	-	5.11	0.20	[27]
<i>Symphonia globustifera</i>	Sambogum	9.49	-	-	-	-	0.97	1.03	[27]
<i>Syzygium wesas</i>	White Eungella satinash	-	-	-	0.17	-	-	-	[14]
<i>Tabebuia chrysantha</i>	Guayacán negro	-	-	-	0.19	-	5.11	0.20	[27]
<i>Tabebuia donnell-smithii</i>	Gold tree	-	-	-	-	-	2.80	0.36	[47]
<i>Tabebuia guayacan</i>	Guayacán	-	-	-	0.13	-	6.81	0.15	[27]
<i>Tabebuia pentaphylla</i>	Roble de sabana	-	-	-	0.44	-	0.97	1.03	[27]
<i>Tabebuia rosea</i>	Rosy trumpet tree	-	-	-	-	-	2.24	0.54	[47]
<i>Talauma dixonii</i>	Cucharillo	4.61	-	-	-	2.06	2.06	0.49	[38]
<i>Talauma dixonii</i>	Cucharillo sw	3.05	-	-	-	0.71	0.71	1.41	[38]
<i>Tectona grandis</i>	Teak	12.65	1.68	21.25	0.16	1.40	7.83	0.10	[7,27,35,37,39,40,49,67]
<i>Tectona grandis</i>	Teak sw	5.42	-	-	-	1.03	1.03	0.97	[-] ¹
<i>Terminalia amazonia</i>	Amarillo	-	-	-	0.25	-	2.91	0.34	[27]
<i>Terminalia catappa</i>	Almond	-	-	-	0.44	-	0.97	1.03	[27]
<i>Terminalia myriocarpa</i>	Dalienze	-	-	-	0.44	-	0.97	1.03	[27]

Table 1. Cont.

Wood Species	Common Name	Above-Ground				In-Ground			References
		k_{inh}	k_{wa}	$D_{Rd,rel.}$	$v_{rel.}$	$k_{inh,soil,lab}$	$D_{Rd,rel.}$	$v_{rel.}$	
<i>Ternstroemia seemannii</i>	Manglillo	-	-	-	0.44	-	0.97	1.03	[27]
<i>Tetragastris panamensis</i>	Anime	-	-	-	0.25	-	2.91	0.34	[27]
<i>Tetrathylacium johansenii</i>	Macho	-	-	-	1.32	-	0.39	2.58	[27]
<i>Tilia americana</i>	Basswood	-	-	-	2.00	-	-	-	[26]
<i>Tilia americana sw</i>	Basswood sw	-	-	-	1.60	-	-	-	
<i>Tilia cordata</i>	Lime	1.18	0.89	1.05	0.86	-	1.39	0.72	[7]
<i>Trattinickia aspera</i>	Caraño	-	-	-	1.32	-	0.97	1.03	[27]
<i>Trichilia tuberculata</i>	Alfaje	-	-	-	0.44	-	0.97	1.03	[27]
<i>Ulmus glabra</i>	Wych elm	2.94	0.96	2.83	0.39	-	1.66	0.60	[7,52]
<i>Vatairea sp.</i>	Amargo-amargo	-	-	-	0.25	-	2.91	0.34	[27]
<i>Viola spp.</i>	Chalviande	-	-	-	-	0.71	0.71	1.41	[38]
<i>Viola koschnyi</i>	Bogamani	-	-	-	1.32	-	0.97	1.03	[27]
<i>Viola serbifera</i>	Mancha	-	-	-	1.32	-	0.39	2.58	[27]
<i>Vitex floridula</i>	Cuajado	-	-	-	0.44	-	0.97	1.03	[27]
<i>Vochysia ferruginea</i>	Mayo	-	-	-	0.44	-	1.94	0.52	[27]
<i>Vouacapoua americana</i>	Acapú	-	-	-	0.06	-	10.22	0.10	[27]
<i>Zanthoxylum belizense</i>	Acabú	-	-	-	0.44	-	0.97	1.03	[27]

¹ unpublished data by the authors.

Table 2. Parameters for predicting the material resistance of untreated softwoods in- and above-ground. K_{inh} = factor accounting for protective inherent properties based on white rot, brown rot, and soil contact tests; $k_{inh,soil,lab}$ = factor accounting for protective inherent properties based on laboratory test with soil contact and soft rot fungi; k_{wa} = factor accounting for moisture performance (wetting ability); $D_{Rd,rel.}$ = relative resistance dose; $v_{rel.}$ = relative decay rate; sw = sapwood. Calculated $v_{rel.}$ in italics.

Wood Species	Common Name	Above-Ground				In-Ground			References
		k_{inh}	k_{wa}	$D_{Rd,rel.}$	$v_{rel.}$	$k_{inh,soil,lab}$	$D_{Rd,rel.}$	$v_{rel.}$	
<i>Abies alba</i>	Silver fir	1.26	0.91	1.14	1.14	1.21	1.24	0.84	[7,30]
<i>Abies balsamea</i>	Balsam fir	-	-	-	-	-	1.23	0.81	[52]
<i>Araucaria cunninghamii</i>	Hoop pine	-	-	1.18	-	-	-	-	[14]
<i>Callitris endlichrei</i>	Black cypress	-	-	0.39	-	-	2.14	0.47	[14]
<i>Callitris endlichrei</i>	Black cypress sw	-	-	0.96	-	-	1.74	0.57	[14]
<i>Callitris glaucophylla</i>	White cypress	-	-	0.32	-	-	3.98	0.25	[14,27]
<i>Callitris glaucophylla</i>	White cypress sw	-	-	1.18	-	-	1.45	0.69	[14]
<i>Chamaecyparis lawsoniana</i>	Port Orford cedar	3.99	-	-	-	1.54	1.54	0.65	[-] ¹
<i>Chamaecyparis lawsoniana</i>	Port Orford cedar sw	1.68	-	-	-	1.30	1.30	0.77	[-] ¹
<i>Chamaecyparis nootkatensis</i>	Yellow cypress	-	-	0.45	-	-	2.97	0.34	[68]
<i>Cupressus x leylandii</i>	Leyland cypress	-	-	-	-	-	2.87	0.35	[52,69]
<i>Juniperus communis</i>	Juniper	10.30	1.17	12.10	0.32	18.00	7.53	0.13	[7,64]
<i>Larix decidua</i>	European larch	3.72	1.51	5.62	0.34	1.16	2.30	0.29	[7,22,23,30,35,39–41,49,52,54,58,59]
<i>Larix decidua</i>	European larch sw	-	-	-	0.93	-	-	-	[7]
<i>Larix laricina</i>	Tamarack	-	-	-	0.57	-	1.76	0.57	[68]
<i>Larix occidentalis</i>	Western larch	-	-	-	0.69	-	2.27	0.44	[68]
<i>Larix sibirica</i>	Siberian larch	3.65	0.96	3.49	0.45	-	4.86	0.21	[7,14,21,35,53,54,70,71]
<i>Metasequoia glyptostroboides</i>	Dawn redwood	3.90	-	-	-	2.16	2.16	0.46	[-] ¹
<i>Metasequoia glyptostroboides</i>	Dawn redwood sw	1.64	-	-	-	0.99	0.99	1.01	[-] ¹
<i>Picea sitchensis</i>	Sitka spruce	1.30	1.79	2.32	0.86	-	1.14	0.88	[7]
<i>Pinus spp.</i>	Southern pine sw	3.75	0.79	2.97	0.76	0.78	0.87	1.00	[7,26,34,36]
<i>Pinus caribaea</i>	Caribbean pine	-	-	-	0.82	-	2.91	0.34	[14,27]
<i>Pinus contorta</i>	Lodgepole pine sw	-	-	-	1.78	-	-	-	[72]
<i>Pinus elliotii</i>	Slash pine	-	-	-	1.13	-	-	-	[14,23]
<i>Pinus elliotii</i>	Slash pine sw	-	-	-	1.28	-	-	-	[14,23]
<i>Pinus pinea</i>	Stone pine sw	-	0.94	-	0.62	-	-	-	[43,73]
<i>Pinus radiata</i>	Radiata pine sw	1.29	0.92	1.19	0.98	1.34	1.16	1.12	[7,35,37]
<i>Pinus resinosa</i>	Red pine sw	-	-	-	1.60	-	-	-	[26]

Table 2. Cont.

Wood Species	Common Name	Above-Ground				In-Ground			References
		k_{inh}	k_{wa}	$D_{Rd,rel.}$	$v_{rel.}$	$k_{inh,soil,lab}$	$D_{Rd,rel.}$	$v_{rel.}$	
<i>Pinus sylvestris</i>	Scots pine	3.39	1.13	3.83	0.47	1.31	1.86	0.53	[7,14,21–23,30,31,35,41,49,52–55,59,71,74,75]
<i>Pinus sylvestris</i>	Scots pine sw	1.05	1.00	1.04	0.83	1.10	1.07	0.95	[7,18,22,23,30,31,34–37,41,49,53–55,58,59,76]
<i>Podocarpus</i> spp.	Podocarpus	1.21	-	-	-	-	-	0.83	[52]
<i>Pseudotsuga menziesii</i>	Douglas fir	4.86	1.66	8.06	0.55	4.27	3.34	0.37	[7,14,23,27,30,35,37,38,41,43,49,54,55,68,75,77,78]
<i>Pseudotsuga menziesii</i>	Douglas fir sw	2.29	1.04	2.39	0.83	1.07	1.43	0.62	[7,26,43,54]
<i>Taxus baccata</i>	Yew	15.69	1.03	16.19	0.06	18.00	15.46	0.08	[39,40,64], [-] ¹
<i>Thuja occidentalis</i>	Eastern white cedar	-	-	-	0.59	-	2.56	0.39	[68,78,79]
<i>Thuja plicata</i>	Western red cedar (N.-America)	8.41	0.90	7.56	0.42	-	2.63	0.38	[7,14,23,33,35,49,68,78]
<i>Thuja plicata</i>	Western red cedar sw (N.-America)	-	-	-	1.45	-	-	-	[7,52]
<i>Thuja plicata</i>	Western red cedar (Europe)	8.33	0.86	7.15	0.35	-	2.11	0.47	[26]
<i>Tsuga heterophylla</i>	Western hemlock	-	-	-	0.94	-	1.15	0.87	[23,52]
<i>Tsuga heterophylla</i>	Western hemlock sw	-	-	-	1.23	-	-	-	[26]

¹ unpublished data by the authors.

Table 3. Parameters for predicting the material resistance of modified timbers in- and above-ground. k_{inh} = factor accounting for protective inherent properties based on white rot, brown rot, and soil contact tests; $k_{inh,soil,lab}$ = factor accounting for protective inherent properties based on laboratory test with soil contact and soft rot fungi; k_{wa} = factor accounting for moisture performance (wetting ability); $D_{Rd,rel.}$ = relative resistance dose; $v_{rel.}$ = relative decay rate; sw = sapwood; TM= thermal modification; OHT = oil-heat treatment; AC = acetylation; FA = furfurylation; DMDHEU = treatment with 1.3-dimethylol-4.5-dihydroxyethyleneurea; WPG = weight percent gain. Calculated $v_{rel.}$ in italics.

Wood Species and Treatment	Above-Ground				In-Ground			References
	k_{inh}	k_{wa}	$D_{Rd,rel.}$	$v_{rel.}$	$k_{inh,soil,lab}$	$D_{Rd,rel.}$	$v_{rel.}$	
<i>Fagus sylvatica</i> —TM	6.64	2.08	13.81	0.02	-	4.68	0.21	[22,58,80]
<i>Larix decidua</i> —TM	-	3.44	-	0.02	-	-	-	[22,58]
<i>Picea abies</i> —TM	4.90	4.23	20.72	0.34	4.38	2.98	0.39	[22,31,34,53,58,66,75,81]
<i>Pinus maritima</i> —TM	4.48	-	-	0.61	5.73	4.63	0.62	[75]
<i>Pinus sylvestris</i> —TM	7.30	1.71	12.47	0.53	11.19	5.36	0.47	[7,18,21,31,36,37,53,66,75,81,82]
<i>Castanea sativa</i> —OHT	-	-	-	-	-	1.70	0.59	[43]
<i>Fraxinus excelsior</i> —OHT	12.82	1.77	22.72	0.07	14.00	11.79	0.19	[7]
<i>P. abies</i> —OHT	13.83	1.37	18.95	0.16	13.49	9.66	0.17	[7,30]
<i>P. sylvestris</i> —OHT	6.69	-	-	0.11	5.36	4.19	0.54	[18,75]
<i>Pseudotsuga menziesii</i> —OHT	-	-	-	-	-	1.92	0.52	[43]
<i>Pinus</i> spp. sw (Southern pine)—AC	17.89	1.31	23.48	0.04	18.00	17.78	0.04	[7]
<i>P. sylvestris</i> / <i>P. radiata</i> sw—AC	17.61	1.82	32.05	0.07	18.00	17.23	0.07	[7,21,37,53,66,82,83]
<i>Acer platanoides</i> —FA	8.14	1.53	12.46	0.05	2.33	3.86	0.12	[7,34,84]
<i>Pinus</i> spp. sw (Southern pine)—FA	9.15	1.45	13.30	0.12	6.01	6.54	0.14	[7,34]
<i>P. sylvestris</i> sw—FA	12.77	1.96	25.06	0.27	6.91	7.53	0.11	[7,21,25]
<i>F. sylvatica</i> —DMDHEU, 20% WPG	-	-	-	0.47	-	1.59	0.63	[29]
<i>F. sylvatica</i> —DMDHEU, 30% WPG	-	-	-	0.12	-	2.65	0.38	[29]
<i>P. sylvestris</i> —DMDHEU, 20% WPG	9.95	1.16	11.52	0.45	10.72	7.34	0.19	[7,24,29,37,82]
<i>P. sylvestris</i> —DMDHEU, 30% WPG	10.69	-	-	0.18	-	6.66	0.15	[29]

¹ unpublished data by the authors.

Table 4. Parameters for predicting the material resistance of preservative-treated timbers in- and above-ground. k_{inh} = factor accounting for protective inherent properties based on white rot, brown rot, and soil contact tests; $k_{inh,soil,lab}$ = factor accounting for protective inherent properties based on laboratory test with soil contact and soft rot fungi; k_{wa} = factor accounting for moisture performance (wetting ability); $D_{Rd,rel.}$ = relative resistance dose; $v_{rel.}$ = relative decay rate; sw = sapwood; CCA = chromated copper arsenate; CCB = chromated copper borate; Cu = copper; EA = ethanolamine; OA = octanoic acid; Quat = quaternary ammonium compounds. Calculated $v_{rel.}$ in italics.

Wood Species and Treatment	Above-Ground				In-Ground			References
	k_{inh}	k_{wa}	$D_{Rd,rel.}$	$v_{rel.}$	$k_{inh,soil,lab}$	$D_{Rd,rel.}$	$v_{rel.}$	
<i>Pinus sylvestris</i> , CCA, 2 kg/m ³	11.56	1.31	15.17	0.10	7.16	5.12	0.18	[7,66,71]
<i>P. sylvestris</i> , CCA, 4 kg/m ³	12.89	1.21	15.61	0.13	6.42	7.79	0.12	[7,25,34,36,53,82]
<i>P. sylvestris</i> , CCA, 9 kg/m ³	12.85	0.94	12.02	0.06	9.56	11.87	0.08	[25,31,34,36,53,66]
<i>Pinus radiata</i> , CCA, 5 kg/m ³	10.68	-	-	-	-	4.25	0.24	[46], [-] ¹
<i>P. radiata</i> , CCA, 10 kg/m ³	-	-	-	-	-	8.22	0.12	[-] ¹
<i>P. radiata</i> , CCA, 13.5 kg/m ³	-	-	-	-	-	8.65	0.12	[-] ¹
<i>Picea abies</i> , Cu (II) sulph. low	5.19	0.93	4.81	0.69	1.82	1.82	0.55	
<i>P. abies</i> , Cu (II) sulph. high	6.16	0.95	5.83	0.63	2.66	2.66	0.38	
<i>P. abies</i> , CuEA low	5.20	1.00	5.21	0.61	2.37	2.37	0.42	
<i>P. abies</i> , CuEA high	4.79	0.97	4.66	0.65	2.00	2.00	0.50	
<i>P. abies</i> , CuEAO low	4.68	1.02	4.78	0.11	1.72	1.72	0.58	
<i>P. abies</i> , CuEAO high	4.36	1.11	4.85	0.57	1.98	1.98	0.51	[24]
<i>P. abies</i> , CuEAOQuat low	6.68	0.92	6.14	0.21	1.45	1.45	0.69	
<i>P. abies</i> , CuEAOQuat high	6.97	0.97	6.79	0.01	1.84	1.84	0.54	
<i>P. abies</i> , BorEAOQuat low	6.00	1.06	6.34	0.86	0.85	0.85	1.18	
<i>P. abies</i> , BorEAOQuat high	5.77	1.80	10.37	0.61	0.88	0.88	1.14	
<i>P. abies</i> , Cu 0.25 %, dip. 8-h	7.60	0.83	6.29	0.58	1.47	1.47	0.68	
<i>P. abies</i> , Cu 0.25 %, dip. 24-h	8.78	0.85	7.44	0.46	1.71	1.71	0.59	
<i>P. abies</i> , Cu 0.25 %, vac.	10.79	0.86	9.29	0.17	3.57	3.57	0.28	
<i>P. abies</i> , Cu 0.25 %, vac. + press.	10.08	0.81	8.17	0.03	4.50	4.50	0.22	
<i>P. abies</i> , Cu 0.5 %, dip. 8-h	8.71	0.85	7.39	0.39	1.54	1.54	0.65	
<i>P. abies</i> , Cu 0.5 %, dip. 24-h	9.59	0.83	7.99	0.42	2.94	2.94	0.34	
<i>P. abies</i> , Cu 0.5 %, vac.	9.24	0.84	7.72	0.13	3.18	3.18	0.32	
<i>P. abies</i> , Cu 0.5 %, vac. + press.	9.37	0.84	7.83	0.15	3.60	3.60	0.28	
<i>P. sylvestris</i> , Cu 0.25 %, dip. 8-h	6.56	1.88	12.35	0.16	1.39	1.39	0.72	[85]
<i>P. sylvestris</i> , Cu 0.25 %, dip. 24-h	7.38	1.10	8.10	0.09	2.38	2.38	0.42	
<i>P. sylvestris</i> , Cu 0.25 %, vac.	10.01	1.31	13.15	0.09	2.01	2.01	0.50	
<i>P. sylvestris</i> , Cu 0.25 %, vac. + press.	10.42	1.01	10.51	0.00	3.03	3.03	0.33	
<i>P. sylvestris</i> , Cu 0.5 %, dip. 8-h	8.34	1.22	10.14	0.13	2.55	2.55	0.39	
<i>P. sylvestris</i> , Cu 0.5 %, dip. 24-h	9.57	1.13	10.80	0.09	2.75	2.75	0.36	
<i>P. sylvestris</i> , Cu 0.5 %, vac.	10.60	1.00	10.65	0.03	3.59	3.59	0.28	
<i>P. sylvestris</i> , Cu 0.5 %, vac. + press.	9.85	1.24	12.24	0.00	3.28	3.28	0.31	
<i>Larix decidua</i> , Cu 0.25 %, dip. 24-h	6.40	4.74	30.35	0.00	1.03	1.03	0.97	
<i>L. decidua</i> , Cu 0.25 %, vac. + press.	9.55	2.15	20.52	0.17	1.10	1.10	0.91	
<i>L. decidua</i> , Cu 0.5 %, dip. 24-h	7.66	1.86	14.25	0.09	1.14	1.14	0.88	[85]
<i>L. decidua</i> , Cu 0.5 %, vac.	9.34	5.31	49.57	0.06	0.87	0.87	1.15	
<i>L. decidua</i> , Cu 0.5 %, vac. + press.	7.85	1.78	13.95	0.20	1.32	1.32	0.76	
<i>P. sylvestris</i> , Cu based, Use class 3	-	-	-	0.12	7.79	6.64	0.19	[7,31,66,82], [-] ¹
<i>P. sylvestris</i> , CCB 6 kg/m ³	9.08	-	-	0.15	9.30	7.77	0.19	[30,75]
<i>P. sylvestris</i> , CCB 17 kg/m ³	15.91	-	-	0.00	18.00	13.83	0.19	[75]
<i>P. sylvestris</i> , metal-free organic	10.21	0.79	8.06	0.09	0.89	2.41	0.21	[7,34]

¹ unpublished data by the authors.

3. Results and Discussion

3.1. Relationship between Relative Decay Rates in- and above-Ground

Decay rates (v , decay rating/year—data not provided) differed remarkably between wood species and treatments, as well as between test methods and particularly between test locations. The test locations were distributed on five different continents and exhibited tropical to boreal climates. To become independent from the climatic conditions at the various field test sites, only the relative decay rates ($v_{rel.}$) were considered for data analysis, with Norway spruce as the reference. The mean $v_{rel.}$ values were determined for each material (Tables 1–4) and were between 3.30 (e.g., sangre, cativo, and panamá) and <0.01 (different copper-treated softwoods) when tested above-ground and between 2.58 (e.g., sangre, gallito, and manzanillo) and 0.04 (acetylated Southern pine) in soil-contact field tests. For materials tested both in- and above-ground, $v_{rel.,soil}$ and $v_{rel.,no soil}$, respectively,

were correlated with each other (Figure 2). As expected, the decay rate, v , was almost always higher in-ground compared to above-ground, for instance by up to factor 3.0 [27] or even factor 12.0 [7]. In contrast, the $v_{rel.}$ (with Norway spruce as reference) was only slightly higher (by factor 1.03) in-ground compared to above-ground test conditions (Figure 2). Furthermore, $v_{rel.,soil}$ and $v_{rel.,no\ soil}$ were linearly correlated (i.e., $R^2 = 0.7684$), but numerous materials still showed large deviations, and since the measure, $v_{rel.}$, itself is relative, the respective absolute decay rates do scatter even more. Therefore, we aimed at establishing a separate material resistance model for wood exposed to ground contact. However, it can be noted that in the absence of either above- or in-ground decay rate data, one could substitute one $v_{rel.}$ for the other. However, if doing so, it is important to take into consideration that this simplification will give rise to a systematic error term.

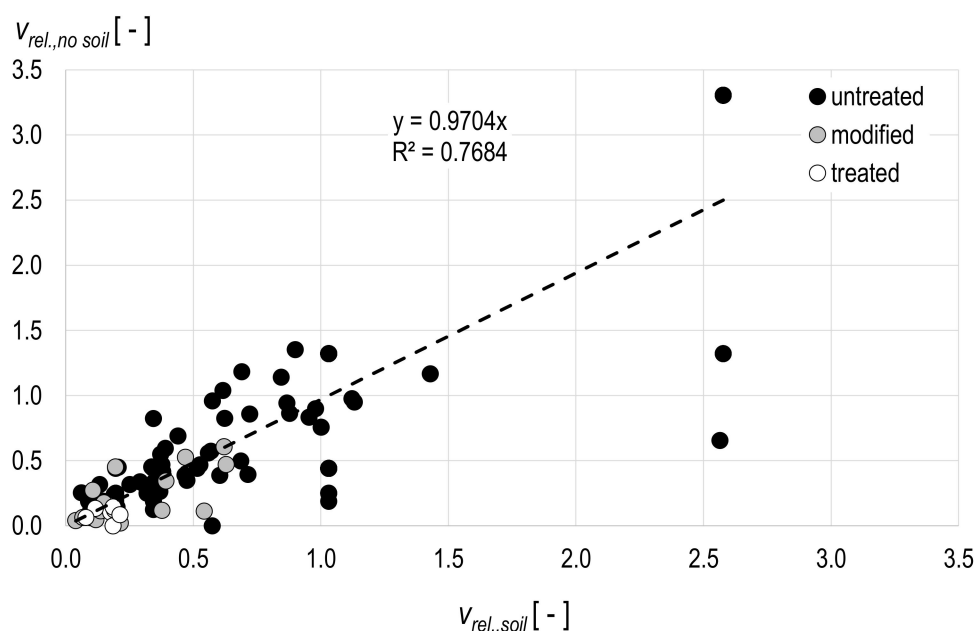


Figure 2. Relationship between calculated relative decay rates ($v_{rel.}$) in-ground contact and above-ground. The basis was 151 untreated timbers, 18 modified and 11 preservative-treated timbers.

3.2. Modelling Material Resistance in Soil Contact

The progress of decay in-ground is less affected by the wetting ability of wood, since wood mainly stays permanently wet when it is exposed to soil [86–88]. Wood that has undergone non-biocidal treatments, aimed at the exclusion of moisture from the cell walls, are therefore often not recommended for use in soil contact where intermediate re-drying is not possible. Similarly, standard laboratory tests with mono-cultures of decay fungi employ permanent wetting, and might be considered as “torture testing” for hydrophobic treatments [89]. Even the mode of protective action of hydrophobized timbers is annulled in laboratory mono-culture tests. Therefore, for the modelling of wood in soil contact, the factor k_{wa} can be neglected, and k_{inh} can be considered exclusively and calculated solely based on soil contact decay tests ($k_{inh,soil}$).

In most cases, $k_{inh,soil}$ was the inverse of $v_{rel.,soil}$, and only k_{inh} values based on laboratory soil contact and/or soft rot tests were used to predict $v_{rel.,soil}$. In Figure 3, both are shown—the relationship between $v_{rel.,soil}$ and all $k_{inh,soil}$ factors, and the $k_{inh,soil,lab}$ factor. The $k_{inh,soil}$ gave a good R^2 , of 0.9407. As expected, the $k_{inh,soil,lab}$ values were less correlated with the $v_{rel.,soil}$ ($R^2 = 0.5129$), but the $k_{inh,soil,lab}$ values were used to predict decay rates of materials for which decay rate data were lacking. These calculated $v_{rel.}$ values are given in italics (Tables 1–4). In total, $v_{rel.,soil}$ was extracted from the data for 163 hardwoods, 31 softwoods, 18 modified timbers, and 41 treated timbers, and $v_{rel.,no\ soil}$ for 166 hardwoods, 27 softwoods, 17 modified timbers, and 38 treated timbers in Tables 1–4.

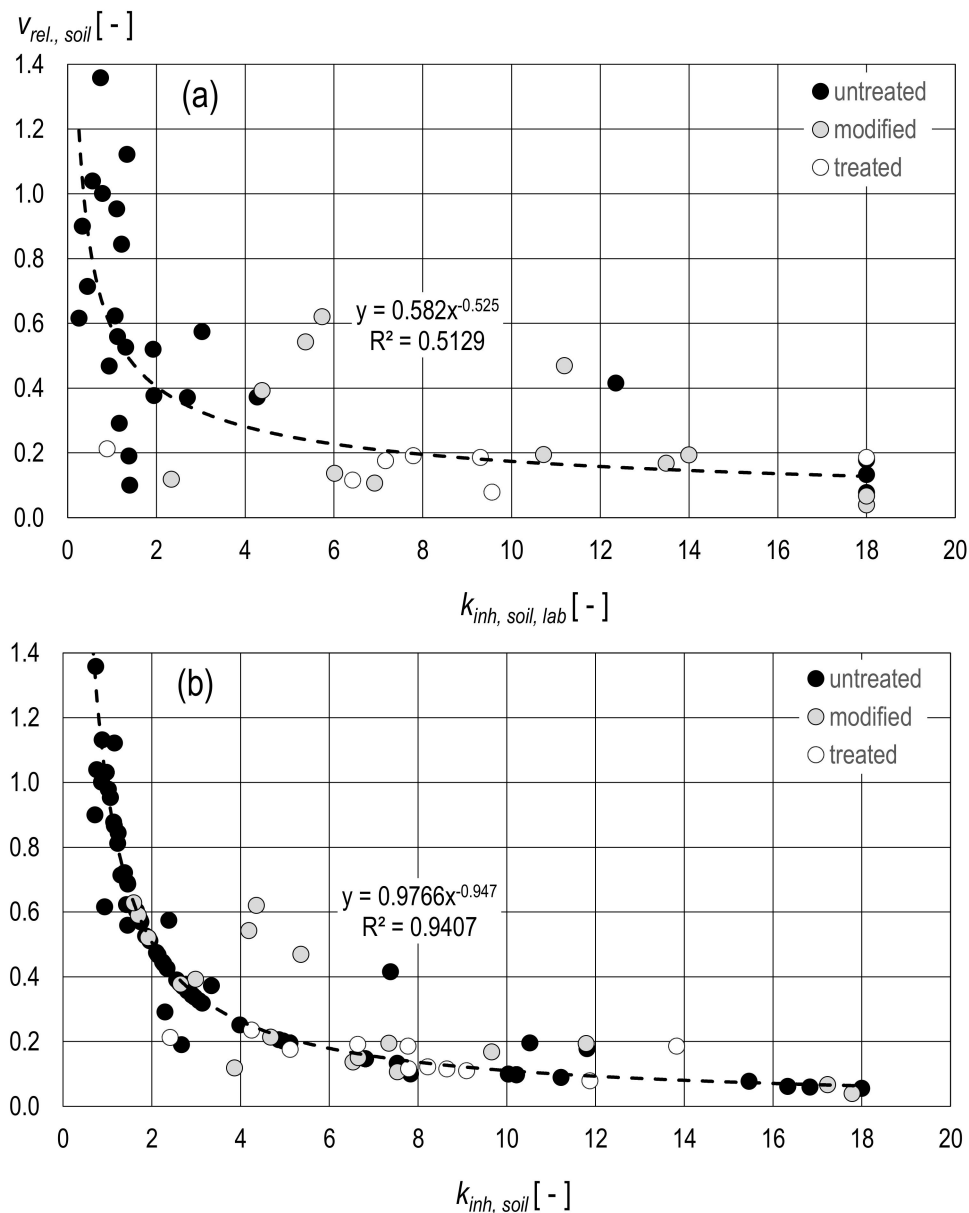


Figure 3. Relationship between relative decay rate in soil contact ($v_{rel.,soil}$) and factors accounting for inherent protective properties in soil contact. (a) Excluding field test data ($k_{inh,soil,lab}$), and (b) including field test data ($k_{inh,soil}$). The basis was (a) 27 untreated, 12 modified and 7 preservative-treated timbers, and (b) 168 untreated, 18 modified and 11 preservative treated-timbers, respectively.

4. Conclusions

From the data meta-analysis, we concluded the following:

- For the first time, a global survey was performed to summarize decay performance in above- and in-ground situations;
- The material resistance was quantified for a high number of wood species and treated timbers, and was expressed in terms of a relative material resistance dose, $D_{Rd,rel.}$ with Norway spruce as the reference species;
- Following systematic comparative studies on the biological durability and the moisture performance of other reference species than Norway spruce, it was possible to increase the amount of exploitable data for modelling;
- Since the material resistance differs significantly between in-ground and above-ground exposure situations, the adapted above-ground model presented in Part 2 of this

publication [10] was further adapted and simplified to predict relative decay rates in soil contact, $v_{rel,soil}$, based on laboratory tests with wood in contact with soil and/or soft rot fungi in a laboratory;

- The use of conversion factors for different reference species implies an additional source of error, and needs to be considered in addition to the natural variation in material resistance and thus the two prediction models;
- This trilogy of papers [9,10] has bridged large knowledge gaps with respect to (1) the increased utilization of decay performance data, and (2) the modelling of the material resistance of wood, both in- and above-ground. Both will facilitate better estimations of service life performance.

Author Contributions: Conceptualization, C.B. and G.A.; Methodology, C.B. and G.A.; Software, C.B. and G.A.; Validation, C.B. and G.A.; Formal Analysis, C.B. and G.A.; Investigation, all authors; Resources, all authors; Data Curation, all authors; Writing—Original Draft Preparation, C.B. and G.A.; Writing—Review & Editing, all authors; Visualization, C.B. and G.A.; Supervision, C.B. and G.A.; Project Administration, C.B., E.S. and G.A.; Funding Acquisition, C.B., G.A., E.S. and S.F. All authors have read and agreed to the published version of the manuscript.

Funding: C.B., G.A., S.F. and E.S. received funding in the frame of the research project CLICKdesign, which is supported under the umbrella of ERA-NET Cofund ForestValue by the Ministry of Education, Science and Sport (MIZS)—Slovenia; The Ministry of the Environment (YM)—Finland; The Forestry Commissioners (FC)—UK; Research Council of Norway (RCN, 297899)—Norway; The French Environment and Energy Management Agency (ADEME) and The French National Research Agency (ANR)—France; The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS), Swedish Energy Agency (SWEA), Swedish Governmental Agency for Innovation Systems (Vinnova)—Sweden; Federal Ministry of Food and Agriculture (BMEL) and Agency for Renewable Resources (FNR)—Germany. ForestValue has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement N° 773324. We acknowledge support by the Open Access Publication Funds of Goettingen University.

Data Availability Statement: The entire set of raw data presented in this study is available on request from the corresponding author.

Acknowledgments: The authors gratefully acknowledge Jonas Niklewski for technical advice on the suitability of data and models for implementation in existing service life prediction framework.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Leicester, R.H.; Wang, C.H.; Nguyen, M.N.; MacKenzie, C.E. Design of exposed timber structures. *Austr. J. Struct. Eng.* **2009**, *9*, 241–248. [CrossRef]
2. Thelandersson, S.; Isaksson, T.; Suttie, E.; Frühwald, E.; Toratti, T.; Grull, G.; Viitanen, H.; Jermer, J. *Service Life of Wood in Outdoor above Ground Applications—Engineering Design Guideline*; Report TVBK-3061; Division of Structural Engineering, Lund University: Lund, Sweden, 2011.
3. Isaksson, T.; Thelandersson, S.; Jermer, J.; Brischke, C. “Beständighet för Utomhusträ Ovan Mark.” *Guide för Utformning och Materialval (Rapport TVBK-3066)*; Division of Structural Engineering, Lund University: Lund, Sweden, 2014.
4. Pousette, A.; Malo, K.A.; Thelandersson, S.; Fortino, S.; Salokangas, L.; Wacker, J. Durable Timber Bridges-Final Report and Guidelines. 2017. Available online: <https://www.diva-portal.org/smash/get/diva2:1116787/fulltext01.pdf> (accessed on 29 March 2021).
5. Niklewski, J. Durability of Timber Members—Moisture Conditions and Service Life Assessment of Bridge Detailing. Doctoral Dissertation, Lund University, Lund, Sweden, 2018.
6. Brischke, C.; Thelandersson, S. Modelling the outdoor performance of wood products—A review on existing approaches. *Constr. Build. Mater.* **2014**, *66*, 384–397. [CrossRef]
7. Meyer-Veltrup, L.; Brischke, C.; Alfredsen, G.; Humar, M.; Flæte, P.O.; Isaksson, T.; Larsson Brelid, P.; Westin, M.; Jermer, J. The combined effect of wetting ability and durability on outdoor performance of wood: Development and verification of a new prediction approach. *Wood Sci. Technol.* **2017**, *51*, 615–637. [CrossRef]
8. Isaksson, T.; Brischke, C.; Thelandersson, S. Development of decay performance models for outdoor timber structures. *Mater. Struct.* **2013**, *46*, 1209–1225. [CrossRef]

9. Alfredsen, G.; Brischke, C.; Marais, B.N.; Stein, R.F.A.; Humar, M. Modelling the Material Resistance of Wood—Part 1: Utilizing Durability Test Data Based on Different Reference Wood Species. *Forests* **2021**, *12*, 558. [[CrossRef](#)]
10. Brischke, C.; Alfredsen, G.; Humar, M.; Conti, E.; Cookson, L.; Emmerich, L.; Flæte, P.O.; Fortino, S.; Francis, L.; Hundhausen, U.; et al. Modelling the material resistance of wood—Part 2: Validation and Optimization of the Meyer-Veltrup Model. *Forests* **2021**, *12*, 576. [[CrossRef](#)]
11. EN 252. *Field Test Method for Determining the Relative Protective Effectiveness of a Wood Preservative in Ground Contact*; European Committee for Standardization: Brussels, Belgium, 2015.
12. EN 113-2. *Durability of Wood and Wood-Based Products—Test Method against Wood Destroying Basidiomycetes—Part 2: Assessment of Inherent or Enhanced Durability*; European Committee for Standardization: Brussels, Belgium, 2020.
13. AWPA E7. *Standard Field Test for Evaluation of Wood Preservatives to be used in Ground Contact (UC4A, UC4B, UC4C), Stake Test*; American Wood Preservers' Association: Hoover, Alabama, 2013.
14. Brischke, C.; Meyer, L.; Alfredsen, G.; Humar, M.; Francis, L.; Flæte, P.O.; Larsson-Brelid, P. Natural durability of timber exposed above ground—A survey. *Drv. Ind.* **2013**, *64*, 113–129. [[CrossRef](#)]
15. ENV 807. *Wood Preservatives—Determination of the Effectiveness against Soft Rotting Micro-Fungi and other Soil Inhabiting Micro-Organisms*; European Committee for Standardization: Brussels, Belgium, 2001.
16. Bravery, A.F. A Miniaturised Wood-Block Test for the Rapid Evaluation of Preservative Fungicides. In *Proceedings of a Special Seminar Held in Association with the 10th Annual Meeting of the IRG, Peebles, Scotland, 18–22 September 1978*; Rep. No. 136; Swedish Wood Preservation Institute: Stockholm, Sweden, 1979.
17. CEN/TS 16818. *Durability of Wood and Wood-Based Products—Moisture Dynamics of Wood and Wood-Based Products*; European Committee for Standardization: Brussels, Belgium, 2018.
18. Welzbacher, C.R.; Rapp, A.O. Determination of the water sorption properties and preliminary results from field tests above ground of thermally modified material from industrial scale processes. In *Proceedings of the IRG Annual Meeting, IRG/WP/04-40279*, Ljubljana, Slovenia, 6–10 June 2004; p. 14.
19. CEN/TS 12037. *Wood Preservatives—Field Test Method for Determining the Relative Protective Effectiveness of a Wood Preservative Exposed out of Ground Contact—Horizontal Lap-Joint Method*; European Committee for Standardization: Brussels, Belgium, 2003.
20. Meyer, L.; Brischke, C.; Preston, A. Testing the durability of timber above ground: A review on methodology. *Wood Mater. Sci. Eng.* **2016**, *11*, 283–304. [[CrossRef](#)]
21. Hundhausen, U.; Flæte, P.O.; Mahnert, K.C.; Bysheim, K. Overflatekvalitet på terrassematerialer—resultater etter to års eksponering. *Tretek. Inf.* **2016**, *1*, 23–27.
22. Humar, M.; Lesar, B.; Kržišnik, D.; Brischke, C. Performance of wood decking after 5 years of exposure: Verification of the combined effect of wetting ability and durability. *Forests* **2019**, *10*, 903. [[CrossRef](#)]
23. Francis, L.P.; Norton, J.; Melcher, E.; Wong, A.H.H.; Kok Lai, J.; Klamer, M.; Konkler, M.J.; Morrell, J.J. Performance of untreated timbers in above ground decking tests: Preliminary results from an international collaborative trial. In *Proceedings of the IRG Annual Meeting, IRG/WP 19-10940*, Quebec City, QC, Canada, 12–16 May 2019; p. 21.
24. Humar, M.; Lesar, B.; Thaler, N. Performance of copper treated and naturally durable wood in laboratory and outdoor conditions. In *Proceedings of the International Conference on Durability of Building Materials and Components, Sao Paulo, Brazil, 2–5 September 2014*; pp. 722–727.
25. Alfredsen, G.; Flæte, P.O.; Militz, H. Performance of Novel Wood Protection Systems—Evaluation Based on Five Different Test Setups. In *Proceedings of the Society of Wood Science and Technology, Geneva, Switzerland, 11–14 October 2010*.
26. Highley, T.L. Comparative durability of untreated wood in use above ground. *Int. Biodeter. Biodegr.* **1995**, *35*, 409–419. [[CrossRef](#)]
27. Bultman, J.D.; Southwell, C.R. Natural resistance of tropical American woods to terrestrial wood-destroying organisms. *Biotropica* **1976**, *8*, 71–212. [[CrossRef](#)]
28. Cookson, L.J.; McCarthy, K.J. Influence of tree age and density on the above-ground natural durability of eucalypt species at Innisfail. *Aust. For.* **2013**, *76*, 113–120. [[CrossRef](#)]
29. Emmerich, L.; Militz, H.; Brischke, C. Long-term performance of DMDHEU-treated wood installed in different test set-ups in ground, above ground and in the marine environment. *Int. Wood Prod. J.* **2020**, *11*, 27–37. [[CrossRef](#)]
30. Augusta, U. *Untersuchung der natürlichen Dauerhaftigkeit wirtschaftlich bedeutender Holzarten bei verschiedener Beanspruchung im Außenbereich*. Doctoral Dissertation, University Hamburg, Hamburg, Germany, 2007.
31. Metsä-Kortelainen, S.; Viitanen, H. Durability of thermally modified sapwood and heartwood of Scots pine and Norway spruce in the modified double layer test. *Wood Mater. Sci. Eng.* **2017**, *12*, 129–139. [[CrossRef](#)]
32. Stirling, R.; Alfredsen, G.; Brischke, C.; De Windt, I.; Francis, L.P.; Frühwald Hansson, E.; Humar, M.; Jermer, J.; Klamer, M.; Kutnik, M.; et al. Global survey on durability variation—On the effect of the reference species. In *Proceedings of the IRG Annual Meeting, IRG/WP 16-20573*, Lisbon, Portugal, 15–19 May 2016; p. 26.
33. Findlay, W.P.K. The natural resistance to decay of some Empire timbers. *Emp. For. J.* **1938**, *17*, 249–259.
34. Westin, M. Durability of furfurylated wood—Results from laboratory and field tests in the Ecobinders project. In *Proceedings of the IRG Annual Meeting, IRG/WP/12-40602*, Kuala Lumpur, Malaysia, 6–10 May 2011; p. 7.
35. Van Acker, J.; De Windt, I.; Li, W.; Van den Bulcke, J. Critical parameters on moisture dynamics in relation to time of wetness as factor in service life prediction. In *Proceedings of the IRG Annual Meeting, IRG/WP/14-20555*, St. George, UT, USA, 11–15 May 2014; p. 22.

36. Westin, M.; Conti, E.; Creemers, J.; Flæte, P.O.; Gellerich, A.; Irbe, I.; Klamer, M.; Melcher, E.; Moeller, R.; Nunes, L.; et al. 10-year Report on COST E37 Round Robin Tests—Comparison of results from laboratory and field tests. In Proceedings of the IRG Annual Meeting, IRG/WP/17-30718, Ghent, Belgium, 4–8 June 2017; p. 13.
37. Emmerich, L.; Brischke, C.; Sievert, M.; Schulz, M.S.; Jaeger, A.C.; Beulshausen, A.; Humar, M. Predicting the outdoor moisture performance of wood based on laboratory indicators. *Forests* **2020**, *11*, 1001. [[CrossRef](#)]
38. Van Acker, J.; Militz, H.; Stevens, M. The significance of accelerated laboratory testing methods determining the natural durability of wood. *Holzforschung* **1999**, *53*, 449–458. [[CrossRef](#)]
39. Wälchli, O. Die Widerstandsfähigkeit verschiedener Holzarten gegen Angriffe durch den echten Hausschwamm (*Merulius lacrimans* (Wulf.) Fr.). *Holz Roh Werkst.* **1973**, *31*, 96–102. [[CrossRef](#)]
40. Wälchli, O. Die Widerstandsfähigkeit verschiedener Holzarten gegen Angriffe durch *Coniophora puteana* (Schum. ex Fr.) Karst. (Kellerschwamm) und *Gloeophyllum trabeum* (Pers. ex Fr.) Murrill (Balkenblättling). *Holz Roh Werkst.* **1976**, *34*, 335–338. [[CrossRef](#)]
41. Brischke, C.; Gellerich, A.; Militz, H.; Starck, M. Performance of coated and uncoated horizontal lap-joint members during 20 years of outdoor exposure. *Wood Res.* **2017**, *62*, 883–894.
42. Militz, H.; Busetto, D.; Hapla, F. Investigation on natural durability and sorption properties of Italian Chestnut (*Castanea sativa* Mill.) from coppice stands. *Holz Roh Werkst.* **2003**, *61*, 133–141. [[CrossRef](#)]
43. Palanti, S. Evaluation of durability conferred by an oleothermic treatment on chestnut and Douglas fir through laboratory and in field tests. *Open J. For.* **2013**, *3*, 66–69.
44. Thaler, N.; Žlahtič, M.; Humar, M. Performance of recent and old sweet chestnut (*Castanea sativa*) wood. *Int. Biodeter. Biodegr.* **2014**, *94*, 141–145. [[CrossRef](#)]
45. Johnson, G.C.; Thornton, J.D.; Trajstman, A.C.; Cookson, L.J. Comparative in-ground natural durability of white and black cypress pines (*Callitris glaucophylla* and *C. endlicheri*). *Aust. For.* **2006**, *69*, 243–247. [[CrossRef](#)]
46. Cookson, L.J. Determining the natural durability of Eucalypts in Australia. In *Durable Eucalypts on Drylands: Protecting and Enhancing Value*; Altaner, C.M., Murray, T.J., Morgenroth, J., Eds.; Marlborough Research Centre: Blenheim, New Zealand, 2017; pp. 77–84.
47. Colín-Urieta, S.; Carrillo-Parra, A.; Rutiaga-Quiñones, J.G.; López-Albarrán, P.; Gabriel-Parra, R.; Ngangyo-Heya, M. Natural durability of seven tropical timber species in ground contact at three sites in México. *J. Trop. For. Sci.* **2018**, *30*, 75–81.
48. Clark, J.W. *Natural Decay Resistance of Fifteen Exotic Woods Imported for Exterior Use*; Forest Products Laboratory Research Paper FPL-RP-103; U.S. Forest Service: Madison, WI, USA, 1969.
49. Van Acker, J.; Stevens, M.; Carey, J.; Sierra-Alvarez, R.; Militz, H.; Le Bayon, I.; Kleist, G.; Peek, R.D. Biological durability of wood in relation to end-use. *Holz Roh Werkst.* **2003**, *61*, 35–45. [[CrossRef](#)]
50. Seehann, G. Zur natürlichen Dauerhaftigkeit von Kempas und Keruing gegenüber holzzerstörenden Pilzen. *Holz Roh Werkst.* **1973**, *31*, 269–272. [[CrossRef](#)]
51. Yamamoto, K.; Hong, L.T. A laboratory method for predicting the durability of tropical hardwoods. *JARQ* **1994**, *28*, 268–275.
52. Smith, G.A.; Orsler, R.J. The biological natural durability of timber in ground contact. In Proceedings of the IRG Annual Meeting, IRG/WP 94-20051, Nusa Dua, Bali, Indonesia, 29 May–3 June 1994; p. 23.
53. Edlund, M.-L. Durability of some alternatives to preservative-treated wood. In Proceedings of the IRG Annual Meeting, IRG/WP 04-30353, Ljubljana, Slovenia, 6–10 June 2004; p. 13.
54. Van den Bulcke, J.; De Windt, I.; Defoirdt, N.; Van Acker, J. Non-destructive evaluation of wood decay. In Proceedings of the IRG Annual Meeting, IRG/WP/11-20479, Queenstown, New Zealand, 8–12 May 2011; p. 11.
55. Brischke, C.; Meyer, L.; Olberding, S. Durability of wood exposed in ground e Comparative field trials with different soil substrates. *Int. Biodeter. Biodegr.* **2014**, *86*, 108–114. [[CrossRef](#)]
56. Brischke, C.; Welzbacher, C.R.; Gellerich, A.; Bollmus, S.; Humar, M.; Plaschkies, K.; Scheiding, W.; Alfredsen, G.; Van Acker, J.; De Windt, I. Wood natural durability testing under laboratory conditions: Results from a round-robin test. *Eur. J. Wood Wood Prod.* **2014**, *72*, 129–133. [[CrossRef](#)]
57. Meyer, L.; Brischke, C.; Melcher, E.; Brandt, K.; Lenz, M.T.; Soetbeer, A. Durability of English oak (*Quercus robur* L.)—Comparison of decay progress and resistance under various laboratory and field conditions. *Int. Biodeter. Biodegr.* **2014**, *86*, 79–85. [[CrossRef](#)]
58. Ugovšek, A.; Šubic, B.; Starman, J.; Rep, G.; Humar, M.; Lesar, B.; Thaler, N.; Brischke, C.; Meyer-Veltrup, L.; Jones, D.; et al. Short-term performance of wooden windows and facade elements made of thermally modified and non-modified Norway spruce in different natural environments. *Wood Mater. Sci. Eng.* **2019**, *14*, 42–47. [[CrossRef](#)]
59. Scheiding, W.; Jacobs, K.; Bollmus, S.; Brischke, C. Durability classification of treated and modified wood—approaching a guideline for sampling, testing, and statistical analysis. In Proceedings of the IRG Annual Meeting, IRG/WP 20-20676, Online Webinar. 10–11 June 2020; p. 8.
60. Ali, A.C. Physical-Mechanical Properties and Natural Durability of Lesser used Wood Species from Mozambique. Doctoral Dissertation, Swedish University of Agricultural Sciences, Uppsala, Sweden, 2011.
61. Reinprecht, L.; Vidholdová, Z. Rot resistance of tropical wood species affected by water leaching. *BioResources* **2019**, *14*, 8664–8677.

62. Deklerck, V.; De Ligne, L.; Espinoza, E.; Beeckman, H.; Van den Bulcke, J.; Van Acker, J. Assessing the natural durability of xylarium specimens: Mini-block testing and chemical fingerprinting for small-sized samples. *Wood Sci. Technol.* **2020**, *54*, 981–1000. [[CrossRef](#)]
63. Deklerck, V.; De Windt, I.; Defoirdt, N.; Van den Bulcke, J.; Beeckman, H.; Espinoza, E.; Van Acker, J. Assessing the natural durability for different tropical timber species using the mini-block test. In Proceedings of the IRG Annual Meeting, IRG/WP 17-10886, Ghent, Belgium, 4–8 June 2017; p. 14.
64. Brischke, C.; Hesse, C.; Meyer-Veltrup, L.; Humar, M. Studies on the material resistance and moisture dynamics of Common juniper, yew, black cherry, and rowan. *Wood Mater. Sci. Eng.* **2018**, *13*, 222–230. [[CrossRef](#)]
65. Conti, E. *English Oak—Natural Durable Timber—Laboratory Test Results*. IRG/WP Durability Database; The International Research Group on Wood Protection, IRG/WP/DDB 14-00014; IRG Secretariat: Stockholm, Sweden, 2014.
66. Westin, M.; Alfredsen, G. Durability of modified wood in UC3 and UC4—Results from lab tests and 5 years testing in 3 fields. In Proceedings of the IRG Annual Meeting, IRG/WP/11-40562, Queenstown, New Zealand, 8–12 May 2011; p. 9.
67. Bavendamm, W.; Anuwongse, B. Über die Fäulnisresistenz thailändischer Holzarten. *Holz Roh Werkst.* **1967**, *25*, 392–393. [[CrossRef](#)]
68. Stirling, R.; Wong, D. Performance of naturally durable decks after 15 years of field exposure. In Proceedings of the IRG Annual Meeting, IRG/WP 20-10963, Online Webinar. 10–11 June 2020; p. 9.
69. Jones, T.G.; Low, C.B.; Meder, R.; O’Callahan, D.R.; Milne, P.G.; Chittenden, C.M.; Ebdon, N.; Dungey, H.S. Heartwood of *Cupressus lusitanica*, *C. macrocarpa*, Leyland and Ovens cypress and prediction of its durability using near-infrared spectroscopy. *Eur. J. Wood Prod.* **2013**, *71*, 183–192. [[CrossRef](#)]
70. Petrenko, I.A. *Stoikost’ Zaboloni i Yadra Listvenitsy Sibirskoi k Porazheniyu Razlichnymi Vidami Domovykh Gribov*; Sibirskii Tekhnologicheskii Institut: Krasnoyarsk, Russia, 1964; pp. 261–264. (In Russian)
71. Venäläinen, M.; Heikkonen, S.; Terziev, N.; Torniaainen, P. Durability of the Siberian larch heartwood timber of different origin: The results of 11-year ground contact test in Finland. *Sib. J. For. Sci.* **2019**, *3*, 14–19, (In English with Russian abstract).
72. Hart, J.H.; Shrimpton, D.M. Role of stilbenes in resistance of wood to decay. *Phytopathology* **1979**, *69*, 1138–1143. [[CrossRef](#)]
73. De Angelis, M.; Romagnoli, M.; Vek, V.; Poljanšek, I.; Oven, P.; Thaler, N.; Lesar, B.; Kržišnik, D.; Humar, M. Chemical composition and resistance of Italian stone pine (*Pinus pinea* L.) wood against fungal decay and wetting. *Ind. Crops Prod.* **2018**, *117*, 187–196. [[CrossRef](#)]
74. Meyer, L.; Brischke, C.; Pilgård, A. Moisture performance based wood durability testing. In Proceedings of the IRG Annual Meeting, IRG/WP 12-20495, Kuala Lumpur, Malaysia, 6–10 May 2012; p. 26.
75. Brischke, C.; Meyer-Veltrup, L. Performance of thermally modified wood during 14 years of outdoor exposure. *Int. Wood Prod. J.* **2016**, *7*, 89–95. [[CrossRef](#)]
76. Brischke, C.; Melcher, E. Performance of wax-impregnated timber out of ground contact: Results from long-term field testing. *Wood Sci. Technol.* **2015**, *49*, 189–204. [[CrossRef](#)]
77. Schulz, G. Vergleichende Untersuchungen mit verschiedenen Stämmen von *Lentinus lepideus*, gleichzeitig ein Beitrag zum Soil-block-Verfahren. *Holz Roh Werkst.* **1958**, *16*, 435–444. [[CrossRef](#)]
78. Morris, P.I.; Ingram, J.; Larkin, G.; Laks, P. Field tests of naturally durable species. *For. Prod. J.* **2011**, *61*, 344–351. [[CrossRef](#)]
79. Conti, E. *Eastern White Cedar—Natural Durable Timber—Laboratory Test Results*. IRG/WP Durability Database; The International Research Group on Wood Protection, IRG/WP/DDB 14-00011; IRG Secretariat: Stockholm, Sweden, 2014.
80. Plaschkies, K.; Scheiding, W.; Jacobs, K.; Rangno, N. Virulence of two Laboratory Test Strains and one Natural Isolate of *Rhodonia (Oligoporus) placenta* against Thermally Modified Pine and Beech Wood. In Proceedings of the IRG Annual Meeting, IRG/WP 13-20524, Stockholm, Sweden, 16–20 June 2013; p. 9.
81. Viitanen, H.; Metsä-Kortelainen, S. Testing of decay resistance of sapwood and heartwood of thermally modified Scots pine and Norway spruce. In Proceedings of the IRG Annual Meeting, IRG/WP/10-40523, Biarritz, France, 9–13 May 2010; p. 10.
82. Alfredsen, G.; Brischke, C.; Meyer-Veltrup, L.; Humar, M.; Flæte, P.-O. The effect of different test methods on durability classification on modified wood. *ProLigno* **2017**, *13*, 290–297.
83. Jacobs, K.; Scheiding, W.; Weiß, B. Durability of acetylated Radiata pine: Laboratory tests and performance in practice. In Proceedings of the IRG Annual Meeting, IRG/WP 20-40899, Online Webinar. 10–11 June 2020; p. 14.
84. Ziethén, R.; Brynildsen, P.; Lande, S.; Kristoffersen, J.; Westin, M. Kebony—An Alternative to Teak for Boat Decking. In *Proceedings of the Fourth European Conference on Wood Modification, Norra Latin City Conference Centre, Stockholm, Sweden, 27–29 April 2009*; SP Technical Research Institute of Sweden: Borås, Sweden.
85. Humar, M.; Lesar, B.; Thaler, N.; Kržišnik, D.; Žlatic, M. Influence of the retention and penetration of Cu based preservatives on the performance of softwoods in ground. In *Designing with Bio-Based Building Materials—Challenges and Opportunities*; De Troya, T., Ed.; Book of Abstract from Joint Technical Workshop; National Institute for Agricultural and Food Research and Technology: Madrid, Spain, 2016.
86. Brischke, C.; Wegener, F.L. Impact of water holding capacity and moisture content of soil substrates on the moisture content of wood in terrestrial microcosms. *Forests* **2019**, *10*, 485. [[CrossRef](#)]
87. Marais, B.N.; Brischke, C.; Militz, H. Wood durability in terrestrial and aquatic environments—A review of biotic and abiotic influence factors. *Wood Mater. Sci. Eng.* **2020**, 1–24. [[CrossRef](#)]

-
88. Marais, B.N.; Brischke, C.; Militz, H.; Peters, J.H.; Reinhardt, L. Studies into fungal decay of wood in ground contact—Part 1: The influence of water-holding capacity, moisture content, and temperature of soil substrates on fungal decay of selected timbers. *Forests* **2020**, *11*, 1284. [[CrossRef](#)]
 89. Brischke, C.; Welzbacher, C.R.; Meyer, L.; Bornemann, T.; Larsson-Brelid, P.; Pilgård, A.; Frühwald Hansson, E.; Westin, M.; Rapp, A.O.; Thelandersson, S.; et al. Service Life Prediction of Wooden Components—Part 3: Approaching a Comprehensive Test Methodology. In Proceedings of the IRG Annual Meeting, IRG/WP 11-20464, Queenstown, New Zealand, 8–12 May 2011; p. 25.