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

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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)):

$$\text{Exposure} \leq \text{Resistance} \tag{1}$$

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):

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

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]:

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

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. elliottii*, *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.

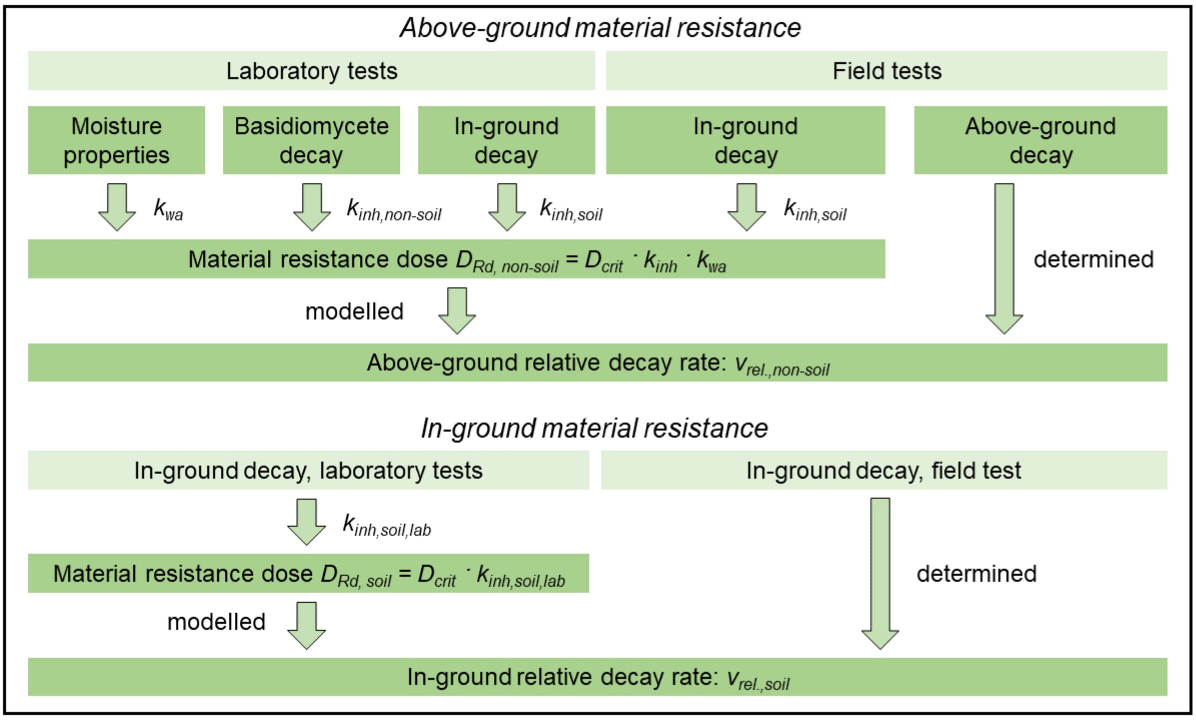

Figure 1. General procedure for determining and modelling relative decay rates, $v_{rel.}$, for in-ground and above-ground exposure conditions. A more detailed edcsription of the different steps is provided in Part 1 and 2 of this publication [9,10].

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 ($k_{inh,non\text{-}soil}$). 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 (-);
$k_{inh,non\text{-}soil,\ j}$ 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)):

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

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

Table 1. *Cont.*

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

Table 1. *Cont.*

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

Table 1. *Cont.*

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

Table 1. *Cont.*

Wood Species	Common Name	Above-Ground				In-Ground			References
		k_{inh}	k_{wa}	$D_{Rd,rel.}$	$v_{rel.}$	$k_{inh,soil,lab}$	$D_{Rd,rel.}$	$v_{rel.}$	
Ternstroemia seemannii	Manglillo	-	-	-	0.44	-	0.97	1.03	[27]
Tetragastris panamensis	Anime	-	-	-	0.25	-	2.91	0.34	[27]
Tetrathylacium johansenii	Macho	-	-	-	1.32	-	0.39	2.58	[27]
Tilia americana	Basswood	-	-	-	2.00	-	-	-	[26]
Tilia americana sw	Basswood sw	-	-	-	1.60	-	-	-	
Tilia cordata	Lime	1.18	0.89	1.05	0.86	-	1.39	0.72	[7]
Trattinickia aspera	Caraño	-	-	-	1.32	-	0.97	1.03	[27]
Trichilia tuberculata	Alfaje	-	-	-	0.44	-	0.97	1.03	[27]
Ulmus glabra	Wych elm	2.94	0.96	2.83	0.39	-	1.66	0.60	[7,52]
Vatairea sp.	Amargo-amargo	-	-	-	0.25	-	2.91	0.34	[27]
Virola spp.	Chalviande	-	-	-	-	0.71	0.71	1.41	[38]
Virola koschnyi	Bogamani	-	-	-	1.32	-	0.97	1.03	[27]
Virola serbifera	Mancha	-	-	-	1.32	-	0.39	2.58	[27]
Vitex floridula	Cuajado	-	-	-	0.44	-	0.97	1.03	[27]
Vochysia ferruginea	Mayo	-	-	-	0.44	-	1.94	0.52	[27]
Vouacapoua americana	Acapú	-	-	-	0.06	-	10.22	0.10	[27]
Zanthoxylum belizense	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}	$D_{Rd,rel.}$	$v_{rel.}$	$k_{inh,soil,lab}$	$D_{Rd,rel.}$	$v_{rel.}$	
Abies alba	Silver fir	1.26	0.91	1.14	1.14	1.21	1.24	0.84	[7,30]
Abies balsamea	Balsam fir	-	-	-	-	-	1.23	0.81	[52]
Araucaria cunninghammii	Hoop pine	-	-	1.18	-	-	-	-	[14]
Callitris endlichrei	Black cypress	-	-	0.39	-	-	2.14	0.47	[14]
Callitris endlichrei	Black cypress sw	-	-	0.96	-	-	1.74	0.57	[14]
Callitris glaucophylla	White cypress	-	-	0.32	-	-	3.98	0.25	[14,27]
Callitris glaucophylla	White cypress sw	-	-	1.18	-	-	1.45	0.69	[14]
Chamaecyparis lawsoniana	Port Orford cedar	3.99	-	-	-	1.54	1.54	*0.65*	[-] [1]
Chamaecyparis lawsoniana	Port Orford cedar sw	1.68	-	-	-	1.30	1.30	*0.77*	[-] [1]
Chamaecyparis nootkatensis	Yellow cypress	-	-	0.45	-	-	2.97	0.34	[68]
Cupressus x leylandii	Leyland cypress	-	-	-	-	-	2.87	0.35	[52,69]
Juniperus communis	Juniper	10.30	1.17	12.10	0.32	18.00	7.53	0.13	[7,64]
Larix decidua	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]
Larix decidua	European larch sw	-	-	-	0.93	-	-	-	[7]
Larix laricina	Tamarack	-	-	-	0.57	-	1.76	0.57	[68]
Larix occidentalis	Western larch	-	-	-	0.69	-	2.27	0.44	[68]
Larix sibirica	Siberian larch	3.65	0.96	3.49	0.45	-	4.86	0.21	[7,14,21,35,53,54,70,71]
Metasequoia glyptostroboides	Dawn redwood	3.90	-	-	-	2.16	2.16	*0.46*	[-] [1]
Metasequoia glyptostroboides	Dawn redwood sw	1.64	-	-	-	0.99	0.99	*1.01*	[-] [1]
Picea sitchensis	Sitka spruce	1.30	1.79	2.32	0.86	-	1.14	0.88	[7]
Pinus spp.	Southern pine sw	3.75	0.79	2.97	0.76	0.78	0.87	1.00	[7,26,34,36]
Pinus carribaea	Carribean pine	-	-	-	0.82	-	2.91	0.34	[14,27]
Pinus contorta	Lodgepole pine sw	-	-	-	1.78	-	-	-	[72]
Pinus elliottii	Slash pine	-	-	-	1.13	-	-	-	[14,23]
Pinus elliottii	Slash pine sw	-	-	-	1.28	-	-	-	[14,23]
Pinus pinea	Stone pine sw	-	0.94	-	0.62	-	-	-	[43,73]
Pinus radiata	Radiata pine sw	1.29	0.92	1.19	0.98	1.34	1.16	1.12	[7,35,37]
Pinus resinosa	Red pine sw	-	-	-	1.60	-	-	-	[26]

Table 2. *Cont.*

Wood Species	Common Name	Above-Ground				In-Ground			References
		k_{inh}	k_{wa}	$D_{Rd,rel.}$	$v_{rel.}$	$k_{inh,soil,lab}$	$D_{Rd,rel.}$	$v_{rel.}$	
Pinus sylvestris	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]
Pinus sylvestris	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]
Podocarpus spp.	Podocarpus	1.21	-	-	-	-	-	0.83	[52]
Pseudotsuga menziesii	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]
Pseudotsuga menziesii	Douglas fir sw	2.29	1.04	2.39	0.83	1.07	1.43	0.62	[7,26,43,54]
Taxus baccata	Yew	15.69	1.03	16.19	*0.06*	18.00	15.46	0.08	[39,40,64], [-] [1]
Thuja occidentalis	Eastern white cedar	-	-	-	0.59	-	2.56	0.39	[68,78,79]
Thuja plicata	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]
Thuja plicata	Western red cedar sw (N.-America)	-	-	-	1.45	-	-	-	[7,52]
Thuja plicata	Western red cedar (Europe)	8.33	0.86	7.15	0.35	-	2.11	0.47	[26]
Tsuga heterophylla	Western hemlock	-	-	-	0.94	-	1.15	0.87	[23,52]
Tsuga heterophylla	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}	$D_{Rd,rel.}$	$v_{rel.}$	$k_{inh,soil,lab}$	$D_{Rd,rel.}$	$v_{rel.}$	
Fagus sylvatica—TM	6.64	2.08	13.81	0.02	-	4.68	0.21	[22,58,80]
Larix decidua—TM	-	3.44	-	0.02	-	-	-	[22,58]
Picea abies—TM	4.90	4.23	20.72	0.34	4.38	2.98	0.39	[22,31,34,53,58,66,75,81]
Pinus maritima—TM	4.48	-	-	0.61	5.73	4.63	0.62	[75]
Pinus sylvestris—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]
Castanea sativa—OHT	-	-	-	-	-	1.70	0.59	[43]
Fraxinus excelsior—OHT	12.82	1.77	22.72	0.07	14.00	11.79	0.19	[7]
P. abies—OHT	13.83	1.37	18.95	0.16	13.49	9.66	0.17	[7,30]
P. sylvestris—OHT	6.69	-	-	0.11	5.36	4.19	0.54	[18,75]
Pseudotsuga menziesii—OHT	-	-	-	-	-	1.92	0.52	[43]
Pinus ssp. sw (Southern pine)—AC	17.89	1.31	23.48	0.04	18.00	17.78	0.04	[7]
P. sylvestris/*P. radiata* sw—AC	17.61	1.82	32.05	0.07	18.00	17.23	0.07	[7,21,37,53,66,82,83]
Acer platanoides—FA	8.14	1.53	12.46	0.05	2.33	3.86	0.12	[7,34,84]
Pinus spp. sw (Southern pine—FA	9.15	1.45	13.30	0.12	6.01	6.54	0.14	[7,34]
P. sylvestris sw—FA	12.77	1.96	25.06	0.27	6.91	7.53	0.11	[7,21,25]
F. sylvatica—DMDHEU, 20% WPG	-	-	-	0.47	-	1.59	0.63	[29]
F. sylvatica—DMDHEU, 30% WPG	-	-	-	0.12	-	2.65	0.38	[29]
P. sylvestris—DMDHEU, 20% WPG	9.95	1.16	11.52	0.45	10.72	7.34	0.19	[7,24,29,37,82]
P. sylvestris—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}	$D_{Rd,rel.}$	$v_{rel.}$	$k_{inh,soil,lab}$	$D_{Rd,rel.}$	$v_{rel.}$	
Pinus sylvestris, CCA, 2 kg/m³	11.56	1.31	15.17	0.10	7.16	5.12	0.18	[7,66,71]
P. sylvestris, CCA, 4 kg/m³	12.89	1.21	15.61	0.13	6.42	7.79	0.12	[7,25,34,36,53,82]
P. sylvestris, CCA, 9 kg/m³	12.85	0.94	12.02	0.06	9.56	11.87	0.08	[25,31,34,36,53,66]
Pinus radiata, CCA, 5 kg/m³	10.68	-	-	-	-	4.25	0.24	[46], [-] [1]
P. radiata, CCA, 10 kg/m³	-	-	-	-	-	8.22	0.12	[-] [1]
P. radiata, CCA, 13.5 kg/m³	-	-	-	-	-	8.65	0.12	[-] [1]
Picea abies, Cu (II) sulph. low	5.19	0.93	4.81	0.69	1.82	1.82	0.55	[24]
P. abies, Cu (II) sulph. high	6.16	0.95	5.83	0.63	2.66	2.66	0.38	
P. abies, CuEA low	5.20	1.00	5.21	0.61	2.37	2.37	*0.42*	
P. abies, CuEA high	4.79	0.97	4.66	0.65	2.00	2.00	*0.50*	
P. abies, CuEAOA low	4.68	1.02	4.78	0.11	1.72	1.72	*0.58*	
P. abies, CuEAOA high	4.36	1.11	4.85	0.57	1.98	1.98	*0.51*	
P. abies, CuEAOAQuat low	6.68	0.92	6.14	0.21	1.45	1.45	*0.69*	
P. abies, CuEAOAQuat high	6.97	0.97	6.79	0.01	1.84	1.84	*0.54*	
P. abies, BorEAOAQuat low	6.00	1.06	6.34	0.86	0.85	0.85	*1.18*	
P. abies, BorEAOAQuat high	5.77	1.80	10.37	0.61	0.88	0.88	*1.14*	
P. abies, Cu 0.25 %, dip. 8-h	7.60	0.83	6.29	0.58	1.47	1.47	*0.68*	[85]
P. abies, Cu 0.25 %, dip. 24-h	8.78	0.85	7.44	0.46	1.71	1.71	*0.59*	
P. abies, Cu 0.25 %, vac.	10.79	0.86	9.29	0.17	3.57	3.57	*0.28*	
P. abies, Cu 0.25 %, vac. + press.	10.08	0.81	8.17	0.03	4.50	4.50	*0.22*	
P. abies, Cu 0.5 %, dip. 8-h	8.71	0.85	7.39	0.39	1.54	1.54	*0.65*	
P. abies, Cu 0.5 %, dip. 24-h	9.59	0.83	7.99	0.42	2.94	2.94	*0.34*	
P. abies, Cu 0.5 %, vac.	9.24	0.84	7.72	0.13	3.18	3.18	*0.32*	
P. abies, Cu 0.5 %, vac. + press.	9.37	0.84	7.83	0.15	3.60	3.60	*0.28*	
P. sylvestris, Cu 0.25 %, dip. 8-h	6.56	1.88	12.35	0.16	1.39	1.39	*0.72*	
P. sylvestris, Cu 0.25 %, dip. 24-h	7.38	1.10	8.10	0.09	2.38	2.38	*0.42*	
P. sylvestris, Cu 0.25 %, vac.	10.01	1.31	13.15	0.09	2.01	2.01	*0.50*	
P. sylvestris, Cu 0.25 %, vac. + press.	10.42	1.01	10.51	0.00	3.03	3.03	*0.33*	
P. sylvestris, Cu 0.5 %, dip. 8-h	8.34	1.22	10.14	0.13	2.55	2.55	*0.39*	
P. sylvestris, Cu 0.5 %, dip. 24-h	9.57	1.13	10.80	0.09	2.75	2.75	*0.36*	
P. sylvestris, Cu 0.5 %, vac.	10.60	1.00	10.65	0.03	3.59	3.59	*0.28*	
P. sylvestris, Cu 0.5 %, vac. + press.	9.85	1.24	12.24	0.00	3.28	3.28	*0.31*	
Larix decidua, Cu 0.25 %, dip. 24-h	6.40	4.74	30.35	0.00	1.03	1.03	*0.97*	[85]
L. decidua, Cu 0.25 %, vac. + press.	9.55	2.15	20.52	0.17	1.10	1.10	*0.91*	
L. decidua, Cu 0.5 %, dip. 24-h	7.66	1.86	14.25	0.09	1.14	1.14	*0.88*	
L. decidua, Cu 0.5 %, vac.	9.34	5.31	49.57	0.06	0.87	0.87	*1.15*	
L. decidua, Cu 0.5 %, vac. + press.	7.85	1.78	13.95	0.20	1.32	1.32	*0.76*	
P. sylvestris, Cu based, Use class 3	-	-	-	0.12	7.79	6.64	0.19	[7,31,66,82], [-] [1]
P. sylvestris, CCB 6 kg/m³	9.08	-	-	0.15	9.30	7.77	0.19	[30,75]
P. sylvestris, CCB 17 kg/m³	15.91	-	-	0.00	18.00	13.83	0.19	[75]
P. sylvestris., 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.

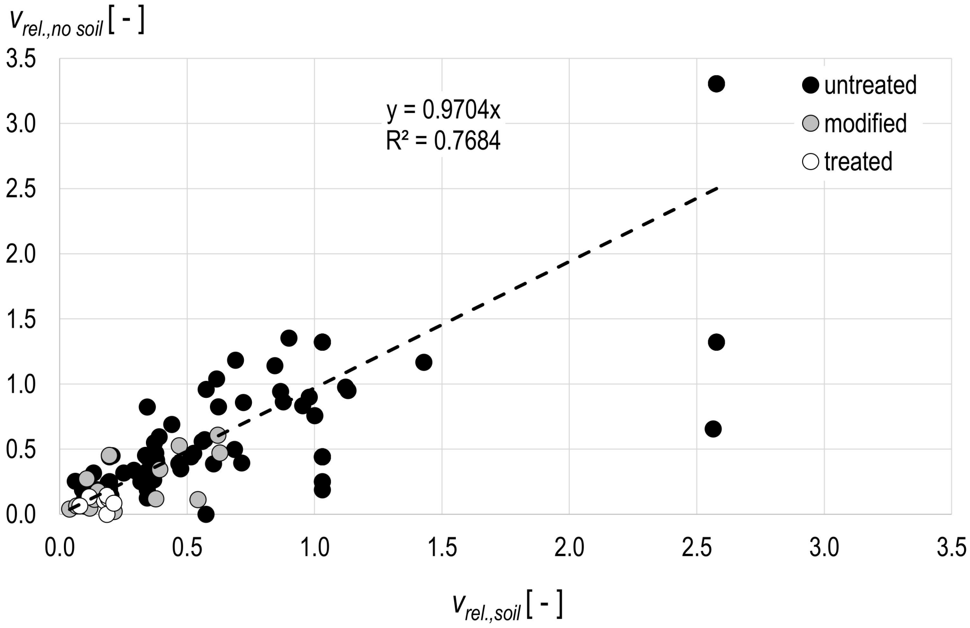

Figure 2. Relationship between calculated relative decay rates (v_{rel}.) in ground contact and above-ground. The basis was 151 untreated timbers, 18 modified and 11 preservative-treated timbers.

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.

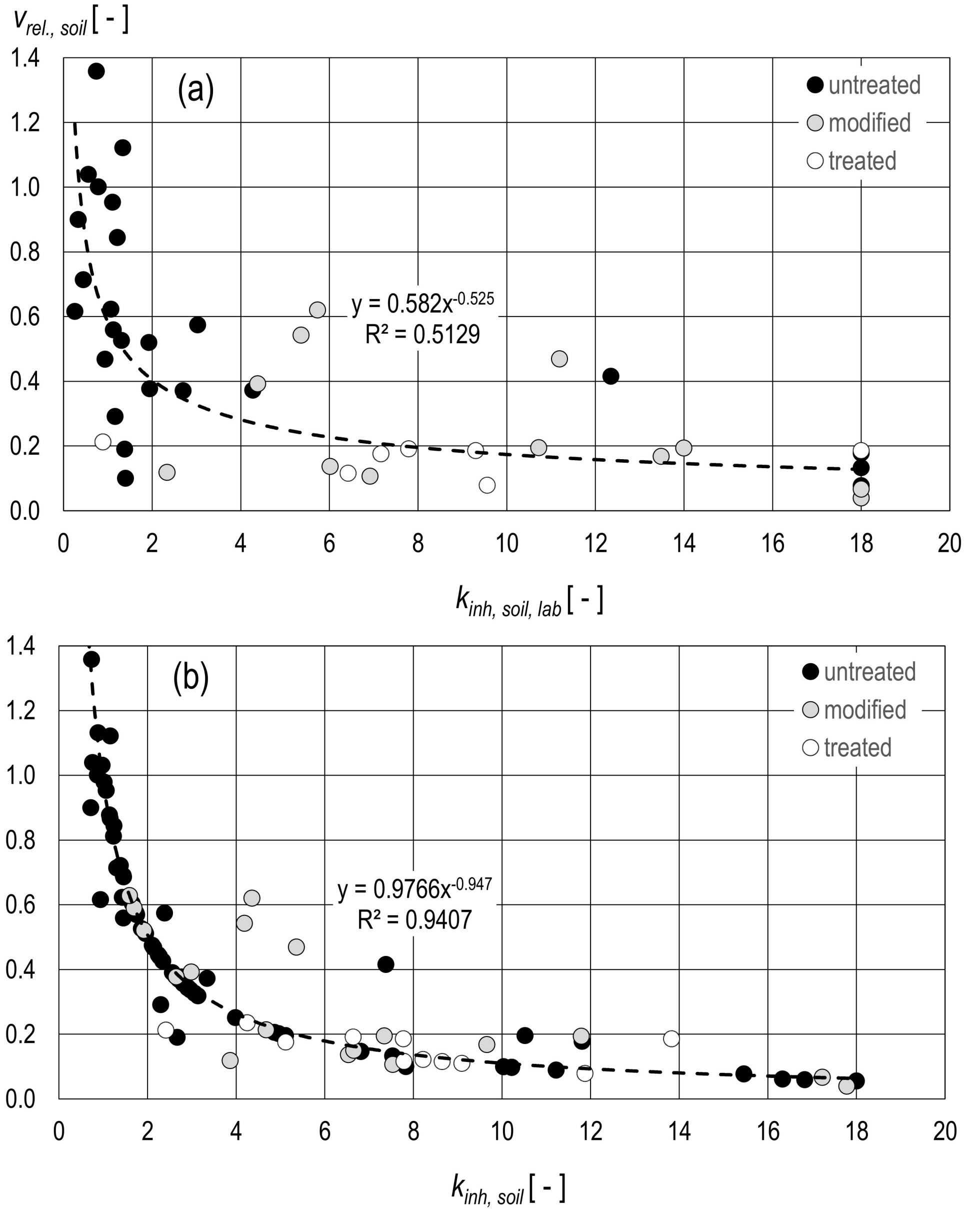

Figure 3. Relationship between relative decay rate in soil contact ($v_{rel.,soil}$) and factors accounting for inherent protective properties in soil contact. (**a**) Excluding field test data ($k_{inh,soil,lab}$), and (**b**) including field test data ($k_{inh,soil}$). The basis was (**a**) 27 untreated, 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.

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