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Modelling the Material Resistance of Wood—Part 1: Utilizing Durability Test Data Based on Different Reference Wood Species

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Abstract: To evaluate the performance of new wood-based products, reference wood species with known performances are included in laboratory and field trials. However, different wood species vary in their durability performance, and there will also be a within-species variation. The primary aim of this paper was to compare the material resistance against decay fungi and moisture performance of three European reference wood species, i.e., Scots pine sapwood (*Pinus sylvestris*), Norway spruce (*Picea abies*), and European beech (*Fagus sylvatica*). Wood material was collected from 43 locations all over Europe and exposed to brown rot (*Rhodonia placenta*), white rot (*Trametes versicolor*) or soft rot fungi. In addition, five different moisture performance characteristics were analyzed. The main results were the two factors accounting for the wetting ability (k_{wa}) and the inherent protective properties of wood (k_{inh}), factors for conversion between Norway spruce vs. Scots pine sapwood or European beech for the three decay types and four moisture tests, and material resistance dose (D_{Rd}) per wood species. The data illustrate that the differences between the three European reference wood species were minor, both with regard to decay and moisture performance. The results also highlight the importance of defined boundaries for density and annual ring width when comparing materials within and between experiments. It was concluded that with the factors obtained, existing, and future test data, where only one or two of the mentioned reference species were used, can be transferred to models and prediction tools that use another of the reference species.

Keywords: basidiomycetes; durability; brown rot; fungal decay; moisture dynamics; soft rot; white rot

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1. Introduction

Robust integrated performance classification of wood products and structures is based on the whole set of external parameters—the foundation established for decay, material and integrity aspects, aesthetic limits and performance, and termite/insect performance aspects. The European ForestValue research project CLICK*design* brings together into a unique single software tool diverse models and performance databases associated with decay and integrity, aesthetic function, and termite performance [1]. The basis for predicting service life and decay of wood is a set of dose-response models accounting for exposure and resistance, both expressed as dosage [2] and following well-established engineering principles [3], Equation (1):

$$Exposure\ dose\ (D_{Ed}) \leq\ Resistance\ dose\ (D_{Rd}) \quad (1)$$

For predicting the field performance of wood-based materials, the material resistance dose (D_{Rd}) needs to be determined to verify the design condition according to Equation (1). The resistance dose D_{Rd} is considered to be the product of a critical dose (D_{crit}) and two modifying factors considering the wetting ability of wood (k_{wa}) and its inherent durability (k_{inh}). The approach to do this is, according to [4], Equation (2):

$$D_{Rd} = D_{crit} \times k_{wa} \times k_{inh} \text{ [d]} \quad (2)$$

where:

D_{Rd} is the material resistance dose [d];
D_{crit} is the critical dose [d] corresponding to decay rating 1 (EN 252 [5]);
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.

The critical dose D_{crit} was evaluated for Scots pine sapwood (*Pinus sylvestris*) and Douglas-fir heartwood (*Pseudotsuga menziesii*) according to [4] based on long-term field tests using horizontal above-ground, double-layer set-ups, which had been exposed and monitored at 25 different locations in Europe [6]. It was found that D_{crit} corresponding to decay rating 1, i.e., 'slight decay', can be seen as more or less independent from the wood species. Instead, differences between species and/or treatments can be accounted for by defining differences in moisture uptake and decay inhibiting properties. For the two wood species, D_{crit} was found to be around 325 days with favorable conditions for fungal decay [4].

Meyer-Veltrup et al. [7] further developed and optimized this model considering the resistance of wood against brown, white and soft rot, as well as relevant types of water uptake and release. They determined factors k_{wa} and k_{inh} for a wide variety of different wood species and modified wood. Furthermore, the model was validated using data from laboratory and field tests [7–9]. Norway spruce was chosen as reference material, having low amounts of extractives and low durability, but is frequently used outdoors all over Europe.

The approach for modelling the material resistance based on moisture performance and material-intrinsic properties is promising and has been validated for a wide range of different wood species. However, robust data are lacking, especially for preservative-treated wood. Additionally, data on modified, water repellant-treated, and coated wood are sparse. The lack of data is caused by the variety of non-durable reference species used in the standard tests and the different prediction models. This variety also causes statistical uncertainty when analyzing existing data from previous durability tests. Prediction models often used Norway spruce, but the standard reference species in European test protocols, e.g., [5,10] are Scots pine sapwood for softwoods and European beech (*Fagus sylvatica*) for hardwoods. In Australia and New Zealand, the AWPC protocol [11] is quite open regarding reference species "The timber species shall be softwood or hardwood and representative of the country or region of proposed end-use". Radiata pine (*Pinus radiata*) is a commonly used softwood, Tasmanian oak (a species mix of *Eucalyptus regnans*, *Eucalyptus obliqua* or *Eucalyptus delegatensis*) is a commonly used hardwood. For laboratory testing in New Zealand, Radiata pine is used as reference species against brown rot fungi and European beech against white rot fungi. In Australia, low durability sapwood references in laboratory tests include Southern pine sapwood (e.g., *Pinus elliottii*, *Pinus caribaea*, *P. elliottii* x *P. caribaea* hybrid) or Radiata pine sapwood. In the US, the field in-ground tests for stakes [12] and posts [13] use sapwood of Southern pine (*Pinus elliottii*, *P. echinata*, *P. palustris, P. taeda*, *P. serotina*, *P. virginiana*, *P. glabra*) as a reference while the above-ground L-joint test [14] uses sapwood of Ponderosa pine (*Pinus ponderosa*) and the horizontal lap-joint method [15] uses sapwood of *Pinus* spp. or "other softwood species shall be used and defined". The laboratory soil-block test [16] lists non-durable softwood such as Southern pine (*Pinus* spp.) for softwood, and sapwood from a non-durable, medium-density hardwood such as Sweetgum (*Liquidambar styraciflua*) or Yellow-poplar (*Liriodendron tulipifera*) for hardwood test blocks. However, neither of these species is easy to treat and are sometimes substituted with Aspen. The standard for evaluation of natural decay resistance using laboratory decay tests [17] lists as references "Pine sapwood (*Pinus* sp.) (. . .)or some other softwood of comparably low resistance should be prepared if a softwood species or product is being tested. Other materials include sapwood of fir, (*Abies* sp.), spruce (*Picea* sp.) or hemlock (*Tsuga* sp.). If broadleaf species (hardwoods) are evaluated (. . .) sapwood of sweetgum (*Liquidambar* sp.) or other low durability species shall be prepared. Potential hardwood species include beech (*Fagus* sp.), birch (*Betula* sp.) or maple (*Acer* sp.)". In the laboratory soil bed test [18], Birch (*Betula papyrifera*) is the preferred hardwood species, and Southern pine (*Pinus* spp.) or Ponderosa pine (*Pinus ponderosa*) are the preferred softwood species. In Thailand, rubberwood (*Hevea brasiliensis*) and Red gum (*Eucalyptus camaldulensis*) are used as a reference in laboratory tests. According to Japanese Industrial Standards (JIS), the sapwood of the softwood Sugi (*Cryptomeria japonica*) is the standard reference species for both field trials and fungal laboratory tests with brown rot (*Fomitopsis palustris*) and white rot (*Trametes versicolor*), as well as termites (*Coptotermes formosanus*). Some, but not all, of the standards listed above provide guidance regarding the range of annual ring width for test specimens. The European standards recommend 2.5–8 rings per 10 mm, e.g., [5,10] while the American standards tend to have a narrower range, 2–4 rings per 10 mm e.g., [12,16].

In this study, the aims were to: 1. compare the material resistance and moisture performance of the three European reference wood species (Norway spruce, European beech and Scots pine sapwood) with conversion factors as the primary output (this paper), 2. collecting data from durability tests for validating and optimizing the 'Meyer-Veltrup model' for material-resistance [7] and Part 2 of this publication [19], and 3. surveying wood durability test data, utilize them for implementation in a material resistance model, and generate a database for service life prediction of wood products in above and in-ground situations, Part 3 of this publication [20].

2. Materials and Methods

2.1. Wood Specimens

Small clear specimens (free from defects such as cracks, decay, and discoloration) from Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*) sapwood, and European beech (*Fagus sylvatica*) were used for fungal decay tests and moisture performance tests. The sample dimensions used in the different tests are referred to in the respective Sections 2.2–2.4. The wood materials were provided by different research institutions and industry partners, plus frozen Scots pine sapwood material from Zimmer et al. [21]. The material included 43 locations in 11 different European countries, as summarized in Table 1. Due to logistic issues, less material was exposed to capillary water uptake (*CWU*) than to 24 h water uptake and release tests (*W24*) and cell wall saturation ($EMC_{\sim 100\%RH}$).

Annual ring width (*ARW*), initial oven-dry mass, and volume were recorded for specimens used in the fungal decay tests, and initial oven-dry density (ρ_0) was calculated.

2.2. Decay Tests with Pure Basidiomycete Cultures

Laboratory decay resistance tests were conducted according to a modified EN 113-2 [10] protocol as follows: in total, 1543 specimens (Table 1), 15 × 25 × 50 (ax.) mm^3, were oven-dried at 103 ± 2 °C for 48 h, weighed to the nearest 0.001 g, and afterwards conditioned at 20 °C/65% relative humidity (*RH*) until constant mass. After sterilization in an autoclave at 121 °C and 0.24 MPa for 20 min, two specimens of the same species were placed on fungal mycelium in a Kolle flask. To avoid direct contact between wood and overgrown malt agar (4%), stainless steel washers were used. The incubation time was 16 weeks. *Rhodonia placenta* (Fr.) Niemelä, K.H. Larss. and Schigel (strain FPRL 280) and *Trametes versicolor* (L.) Lloyd (strain CTB 863A) were used as test fungi. After incubation, the specimens were cleaned from adhering mycelium, weighed to the nearest 0.001 g, and oven-dry mass loss (ML_f) was calculated according to Equation (3):

$$ML_f = \left(\frac{m_{0,i} - m_{0,f}}{m_{0,i}}\right) \times 100\ [\%] \quad (3)$$

where:

$m_{0,i}$ is the oven-dry mass before incubation (g);
$m_{0,f}$ is the oven-dry mass after incubation (g).

Table 1. Number of replicates used in this study. *R.p.* = *Rhodonia placenta*, *T.v.* = *Trametes versicolor*, TMC = terrestrial microcosm, soft rot test, *W24* = 24 h water uptake and release tests, $EMC_{\sim 100\%RH}$ = cell wall saturation, *CWU* = capillary water uptake. NA = not available.

		Decay			Moisture	
	Location	***R.p.***	***T.v.***	**TMC**	***W24*, $EMC_{\sim 100\%RH}$**	***CWU***
Norway spruce	Rippoldsau, DE	15	15	15	10	9
	Breisgau, DE	15	15	15	10	10
	Eastern Finland, FI	25	25	50	50	50
	Haute Loire, FR	15	15	30	10	9
	Slovenia, SI	20	21	45	30	12
	Ribnica, SI	33	33	89	40	4
	Hobøl, stand 1, NO	5	5	10	10	10
	Hobøl, stand 2, NO	30	30	60	60	60
	Hobøl, stand 3, NO	35	35	70	70	69
	Total Norway spruce:	193	194	384	290	233
Scots pine sapwood	Northern Zealand, DK	15	15	30	10	10
	Tartu, stand 1, EE	25	25	NA	10	5
	Tartu, stand 2, EE	10	10	NA	4	2
	Pudasjärvi, stand 1, FI	15	15	NA	6	3
	Heinävesi, stand 3, FI	5	5	NA	2	1
	Raseborg, stand 4, FI	15	15	NA	4	3
	Raseborg, stand 5, FI	10	10	NA	4	2
	Eastern Finland, FI	25	25	50	50	50
	St Chély d'apcher, FR	15	15	30	10	10
	Oerrel, DE	15	15	15	10	10
	Halberstadt, DE	15	15	15	10	10
	Unterfranken, DE	15	14	15	10	10
	Klaipeda, stand 1, LT	40	40	NA	16	8
	Rognan, stand 1, NO	5	5	NA	0	0
	Berkåk, stand 2, NO	5	5	NA	0	0
	Åkrestrømmen, stand 4, NO	5	5	NA	2	0
	Kongsberg, stand 5, NO	15	15	NA	6	3
	Kongsberg, stand 9, NO	5	5	NA	2	1
	Bergen, stand 7, NO	5	5	NA	2	1
	Bergen, stand 8, NO	5	5	NA	2	1
	Harads, stand 4, SE	15	15	NA	6	3
	Borås, stand 5, SE	20	20	NA	6	4
	Borås, stand 6, SE	10	10	NA	4	2
	Forres, stand 1, Scotland, GB	10	10	NA	4	2
	Munlochy, stand 2, Scotland, GB	30	30	NA	12	6
	Alves, Scotland, GB	60	60	120	40	36
	Slovenia, SI	21	22	45	30	8
	Northern Spain, ES	15	15	69	10	8
	Total Scots pine sapwood:	446	446	389	272	199
European beech	Haute Saône, FR	15	15	30	10	10
	Reinhausen, DE	15	15	15	10	10
	Slovenia, SI	21	21	45	30	8
	Switzerland, CH	21	21	75	30	8
	Northern Spain, ES	15	15	NA	0	10
	Denmark, DK	45	45	90	30	30
	Total beech:	132	132	255	110	76
	Total specimens per test:	771	772	1028	672	508

2.3. Decay Tests in Terrestrial Microcosms (TMCs)

Terrestrial microcosms (TMCs), in accordance with CEN/TS 15083-2 [22], were utilized in semi-field experiments. The soil moisture content (MC_{soil}) was equal to 95% of the soil-water holding capacity (WHC_{soil}), and the test was conducted in a dark, climate-controlled room set to a temperature of 27 °C and 65% RH. Wood specimens of 5 × 10 × 100 (ax.) mm^3, a total of 1028, were buried 4/5 of their length into the soil substrate with 58 specimens per TMC box. The incubation time was 16 weeks. The ML_f was calculated according to Equation (3). Details about the soil preparation are provided below.

2.3.1. Soil Substrates

The basis of the substrate was a horticultural compost produced at the forest botanical garden at the University of Göttingen's North Campus. The compost comprised of fallen leaves and cuttings from grass and trees. Soil was passed through a sieve with nominal aperture size of 8.5 mm. WHC_{soil} was then determined according to the 'cylinder sand bath method' according to ISO 11268-2 [23]. Silica sand (0–0.2 mm grain size) was added to lower the WHC_{soil} of the pure compost substrate and deliver a soil mixture with WHC_{soil} of 60%.

2.3.2. Determination of the Soil Moisture Content (MC_{soil})

Soil samples of 50–90 g (depending on the soil density) were taken for determining the MC_{soil}. Three replicate samples were taken, weighed to the nearest 0.01 g, oven-dried at 103 °C for 24 h, and weighed again. MC_{soil} was calculated according to Equation (4):

$$MC_{soil} = \left(\frac{m_w - m_0}{m_0} \right) \times 100 \quad (4)$$

where:

MC_{soil} is the soil moisture content (%);
m_w is the wet soil mass (g);
m_0 is the oven-dry soil mass (g).

2.3.3. Determination of the Soil-Water Holding Capacity (WHC_{soil})

Soil was inserted into hollow polyethylene cylinders 10 cm long with 4 cm diameter. The bottoms of the cylinders were covered with a fine polymer grid and filter paper (MN 640 W 70 mm). All cylinders were filled with soil to a height of 5–7 cm and saturated in an 8 cm high water bath for 3 h. After the saturation period, the cylinders were placed on a water saturated sand bath for 2 h to allow unbound water within the soil-filled cylinders to drain to reach the equivalent of field capacity. The soil samples were then weighed wet, as well as after oven-drying at 103 ± 2 °C for 24 h. WHC_{soil} (%) was calculated according to Equation (5):

$$WHC_{soil} = \left(\frac{m_s - m_0}{m_0} \right) \times 100 \quad (5)$$

where:

WHC_{soil} is the soil water-holding capacity (%);
m_s is the saturated soil mass (g);
m_0 is the oven-dry soil mass (g).

2.3.4. Preparation of Mixed Soil Substrate

To mix the different soil substrates of compost and sand to the predetermined WHC_{soil} of 60%, the WHC_{soil} of soils mixed in incremental ratios based on oven-dry mass was first determined.

Table 2 below shows the incremental soil mixtures used to establish a WHC_{soil} regression equation for the substrates sand and compost. To prepare mixed soil substrates for testing WHC_{soil}, Equation (6) below was used.

$$m_{x,wet} = m_{total,dry} \times \left(\frac{x}{100}\right) \times \left(1 + \frac{MC_x}{100}\right) \quad (6)$$

where:

$m_{x,\,wet}$ is the mass of the wet substrate x (g);
$m_{total,\,dry}$ is the oven-dry mass of the total soil mixture (g);
x is the fraction of the substrate (sand or compost) in the total soil mixture $m_{total,\,dry}$ based on oven-dry mass (%);
MC_x is the moisture content of the soil substrate x (%).

Table 2. Mixing ratios of soil substrates for WHC_{soil} of mixed soil substrates. Percentage is based on the oven-dry soil mass (g).

	Resultant WHC_{soil} (%)										
Equation (7)	100	93	86	79	72	65	58	51	44	37	30
Percentage compost (%)	100	90	80	70	60	50	40	30	20	10	0
Percentage sand (%)	0	10	20	30	40	50	60	70	80	90	100

A regression between the incremental mixing ratios of the two substrates sand and compost and their resulting WHC_{soil} was determined. Equation (7) below shows the regression relationship for WHC_{soil} of the two substrates used to define the mixture percentages to attain a mixed soil substrate with WHC_{soil} 60%. Table 2 below shows the output from computations using Equation (7).

$$WHC_{soil} = 0.7x + 30 \quad (7)$$

where:

WHC_{soil} is the target water-holding capacity of the soil mixture (%);
x is the fraction of pure compost substrate in the total soil mixture based on oven-dry mass (%).

2.3.5. Preparation of Mixed Soil to Reach Target Soil Moisture Content ($MC_{soil,target}$)

A soil mixture with WHC_{soil} of 60% was attained in a ratio of 43% compost to 57% silica sand, weighing a total of 8500 g (based on oven-dry mass). Then, in accordance with CEN/TS 15083-2 [22], distilled water was added to the soil mixture to reach MC_{soil} equal to 95%WHC_{soil}, shown here as the target soil moisture content ($MC_{soil,target}$) of 57%. Equation (8) below was used to calculate the mass (g) of distilled water required to add to the soil mixture to reach $MC_{soil,target}$ of 57%. To account for losses in MC_{soil} resulting from fungal activity and evaporation, rewetting to $MC_{soil,target}$ occurred once per week throughout the 16-week incubation period.

$$m_{water} = \left(\frac{MC_{soil,target} - MC_{soil,current}}{100}\right) \times m_{total,\,dry} \quad (8)$$

where:

m_{water} is the mass of distilled water to add to the soil mixture (g);
$MC_{soil,target}$ is the target soil moisture content (%);
$MC_{soil,current}$ is the current moisture content of the soil mixture before adding additional water (%);
$m_{total,\,dry}$ is the oven-dry mass of the total soil mixture (g).

2.4. W24-Tests (24 h Water Uptake and Release Tests)

For all three W24-tests (Sections 2.4.1–2.4.3), the same specimens, a total of 672 (Table 1), were used. The specimen dimension was 5 × 10 × 100 (ax.) mm^3.

2.4.1. Liquid Water Uptake by Submersion (LWU)

The specimens were oven-dried at 103 °C until constant mass. The oven-dry mass was determined to the nearest 0.001 g. Oven-dry specimens were submerged in a sealed plastic container with demineralized water and placed in a climate chamber at 20 °C/65% *RH*. Specimens were separated from each other by square-shaped stainless steel meshes. The specimens were weighed again after 24 h submersion. The liquid water uptake (*LWU*) of the specimens was determined according to Equation (9):

$$LWU = \left(\frac{m_{sub} - m_0}{m_0}\right) \times 100\ [\%] \quad (9)$$

where:

LWU is the liquid water uptake during 24 h submersion (%);
m_0 is the oven-dry mass before submersion (g);
m_{sub} is the mass after 24 h submersion (g).

2.4.2. Water Vapor Uptake in Water-Saturated Atmosphere (*VU*)

The specimens were oven-dried at 103 °C until constant mass. The oven-dry mass was determined to the nearest 0.001 g. The bottom of a miniature climate chamber (sealed plastic container with stainless steel perforated plates) was filled with 5 L of demineralized water. Specimens were placed with approx. 5 mm distance between each other on stainless-steel plates above the water. The containers were stored in a climate chamber (20 °C/65% *RH*), and specimens weighed again after 24 h. The water vapor uptake (*VU*) of the specimens was determined according to Equation (10):

$$VU = \left(\frac{m_{100\%RH} - m_0}{m_0}\right) \times 100\ [\%] \quad (10)$$

where:

VU is the water vapor uptake during 24 h exposure above water (%);
m_0 is the oven-dry mass before submersion (g);
$m_{100\%RH}$ is the mass after 24 h exposure above water (g).

2.4.3. Desorption (*VR*)

Specimens were stored in sealed containers above water at 20 °C (approximately 100% *RH*) until constant mass. The mass at approximate cell wall saturation ($EMC{\sim}_{100\%RH}$) was determined to the nearest 0.001 g. Specimens were exposed directly on freshly activated silica gel in sealed boxes (0% *RH*) and weighed again after 24 h. The water vapor release (desorption) of the specimens during 24 h was determined and expressed as a relative value of the mass at $EMC{\sim}_{100\%RH}$ (Equation (11)):

$$VR = \left(\frac{EMC \sim 100\%RH - m_{0\%RH}}{EMC \sim_{100\%RH}}\right) \times 100[\%] \quad (11)$$

where:

VR is the water vapor release during 24 h exposure at 0% *RH* (%)
$EMC{\sim}_{100\%RH}$ is the mass at cell wall saturation (g)
$m_{0\%RH}$ is the mass after 24 h exposure to 0% *RH* (g)

2.4.4. Capillary Water Uptake (*CWU*)

Short-term water absorption was measured using a Krüss Processor Tensiometer K100MK2 (Krüss GmbH, Hamburg, Germany). A total of 508 specimens (Table 1) with the dimensions 60 (ax.) $\times$ 10 $\times$ 5 mm^3 (wood material from Germany), 100 (ax.) $\times$ 10 $\times$ 5 mm^3 (Scots pine sapwood from [21]) or 30 (ax.) $\times$ 10 $\times$ 5 mm^3 (wood material from the remaining locations) were stored at 20 °C/65% *RH* until a constant mass was reached ($m_{65\%RH}$). For the capillary water uptake tests, the axial specimen surfaces (10 $\times$ 5 mm^2) were fixed in the tensiometer and positioned to be in contact with water (end-grain uptake). The specimen's mass was recorded after 200 s. The *CWU* was determined over time and related to the cross-sectional area of the specimens (Equation (12):

$$CWU = \frac{m_{200s} - m_{65\%RH}}{A} \left[g/cm^2\right] \tag{12}$$

where:

CWU is the capillary water uptake during 200 s (g/cm^2);
m_{200s} is the mass after 200 s in contact with water (g);
$m_{65\%RH}$ is the mass at 20 °C/65% *RH* (g);
A = axial specimen surface.

2.5. Statistical Analyses

The Tukey–Kramer HSD (honestly significant difference) test was used to compare means (JMP Pro 14, SAS Institute Inc., Cary, NC, USA) on a 5% level of significance, due to the unequal sample sizes. Linear regression models (Equation (13)) were used to study the influence of initial oven-dry density (ρ_0), annual ring width, and an interaction term of the latter on different combinations of wood species and decay fungus (Equations (13a)–(13d)). Variables with *p*-values < 5% were considered significant.

$$Y_i = f(X_i, \beta) + e_i \tag{13}$$

where:

Y_i is the response;
f is the function;
X_i is the independent variable;
β are the unknown parameters;
e_i are the error terms.

$$Model\ 1 \quad ML_f = \beta_0 + \beta_1\rho_0 + e_1 \tag{13a}$$

$$Model\ 2 \quad ML_f = \beta_0 + \beta_1 ARW + e_1 \tag{13b}$$

$$Model\ 3 \quad ML_f = \beta_0 + \beta_1\rho_0 + \beta_2 ARW + e_1 \tag{13c}$$

$$Model\ 4 \quad ML_f = \beta_0 + \beta_1\rho_0 + \beta_2 ARW + \beta_3\rho_0 \times ARW + e_1 \tag{13d}$$

where:

ML_f (mass loss) is the response;
β_0 is the population intercept;
β_i is the population slope coefficient;
ρ_0 is the initial oven-dry density;
ARW is the annual ring width;
e_1 are the error terms.

3. Results and Discussion

3.1. Wood Species Level

The total mean mass loss (ML_f) for the three fungal decay tests and the characteristics for the four moisture performance tests (*LWU*, *VU VR*, *CWU*) are summarized in Table 3.

Table 3. Summary of the main findings, factors (in bold) for: the inherent protective properties of wood (k_{inh}), wetting ability (k_{wa}), and conversion from Norway spruce vs. Scots pine sapwood or European beech, and material resistance dose (D_{Rd}) per wood species. sw = sapwood.

		Norway Spruce		Scots Pine sw		European Beech			
		ML_f (%)	k_{inh} (-)	ML_f (%)	k_{inh} (-)	ML_f (%)	k_{inh} (-)	$f_{spruce/pine\ sw}$	$f_{spruce/beech}$
k_{inh}	***R. placenta***	27.17	1.00	30.66	0.89	24.82	1.09	1.13	0.91
	T. versicolor	21.41	1.00	24.94	0.86	29.67	0.72	1.16	1.39
	TMC	19.10	1.00	18.53	1.03	18.87	1.01	0.97	0.99
	k_{inh} ***all***		**1.00**		**0.95**		**0.96**	**1.05**	**1.04**
		W24 (%)	k_{wa} **(-)**	**W24 (%)**	k_{wa} **(-)**	**W24 (%)**	k_{wa} **(-)**		
k_{wa}	**liquid uptake**	61.31	1.00	60.55	1.01	53.70	1.14	0.99	0.88
	vapor uptake	12.17	1.00	13.97	0.87	10.48	1.16	1.15	0.86
	vapor release	16.27	1.00	13.54	0.83	15.99	0.98	1.20	1.02
		CWU **(g/cm^2)**	k_{wa} **(-)**	***CWU*** **(g/cm^2)**	k_{wa} **(-)**	***CWU*** **(g/cm^2)**	k_{wa} **(-)**		
k_{wa}	**capillary uptake**	0.30	1.00	0.29	1.03	0.21	1.43	0.97	0.70
	k_{wa} **all**		**1.00**		**0.94**		**1.18**	1.07	0.85
D_{Rd}			**325**		**290**		**328**		

Table 3 also provides the main findings of this study, i.e.,: (1) the factors k_{inh} and k_{wa}, (2) factors for conversion between Norway spruce vs. Scots pine sapwood or European beech for the three decay types and four moisture tests, and (3) the material resistance dose D_{Rd} per wood species. The results illustrate that the difference in performance between the three reference wood species is small.

When comparing mean ML_f between decay fungi for each wood species, Tukey–Kramer HSD showed significant differences caused by *R. placenta*, *T. versicolor* and TMC when exposed to the same wood species (i.e., Norway spruce, Scots pine sapwood, or European beech). Hence, this confirms why the performance of a wood species must be compared using the same test organisms.

When comparing mean ML_f between wood species exposed to the same test organisms (i.e., *R. placenta*, *T. versicolor* or TMC), the three wood species showed significant differences in mean ML_f after exposure to only *T. versicolor* and *R. placenta.* After exposure to TMC, however, no significant difference in the mean ML_f between the three wood species was found.

According to Stirling et al. [24] "Field tests have been performed around the world for many decades, but unfortunately, most of the data are not available in a form that can be utilised for service life models". This includes the use of different reference species. The first step in comparing global field test performance data (source: IRG Durability Database, https://www.irg-wp.com/durability/index.html (accessed on 1 February 2016)) for non-durable reference species was provided by Stirling et al. [24]. They noted that Norway spruce, Scots pine sapwood and European beech were all suitable for use as reference species, however, slow-grown spruce should be avoided. With this paper, the factor provided in Table 3 takes a big step further for future utilization and comparison of test performance data.

3.2. Location Level-Decay

Table 4 provides an overview of the mean ML_f values for the fungal decay tests for each of the three wood species from every location included in the dataset. Tables 4–6 provide

Tukey–Kramer HSD comparisons of mean ML_f per wood species, between locations. The data strongly indicate that location alone is not a main influencing factor for the durability performance of Norway spruce against the two tested basidiomycetes and soft rot. Therefore, the variation needs to be investigated on a stand or tree level.

Table 4. Mean mass loss (ML_f) and standard deviation from all decay tests at each location. *R.p.* = *Rhodonia placenta*, *T.v.* = *Trametes versicolor*, TMC = terrestrial microcosm, soft rot test, NA = not available, s. = stand.

	Location	ML_f (*R.p.*) [%]		ML_f (*T.v.*) [%]		ML_f (TMC) [%]	
Norway spruce	Rippoldsau DE	27.64	± 1.24	16.91	± 4.04	18.82	± 4.80
	Breisgau DE	30.45	± 2.05	24.71	± 1.39	12.78	± 3.89
	E. Finland FI	26.85	± 2.71	22.39	± 3.39	18.05	± 6.42
	Haute Loire FR	27.50	± 1.81	21.85	± 2.61	24.49	± 5.09
	Slovenia SI	30.95	± 4.12	22.33	± 2.90	20.35	± 5.80
	Ribnica SI	24.39	± 1.64	16.08	± 1.19	16.48	± 4.19
	Hobøl s.1 NO	31.28	± 1.00	27.36	± 3.74	30.57	±9.64
	Hobøl s.2 NO	28.53	± 3.08	23.88	± 4.06	22.36	± 6.45
	Hobøl s.3 NO	24.35	± 2.28	22.53	± 3.49	17.04	± 4.11
	Total mean:	27.17	± 3.46	21.41	± 4.34	19.10	± 6.31
Scots pine sapwood	N. Zealand DK	39.24	± 1.03	23.79	± 4.61	26.55	± 4.99
	Tartu s.1 EE	28.51	± 2.05	26.16	± 2.58	NA	
	Tartu s.2 EE	31.95	± 3.21	23.38	± 1.99	NA	
	Pudasjärvi s.1 FI	29.96	± 1.41	26.85	± 3.37	NA	
	Heinävesi s.3 FI	29.90	± 1.16	26.80	± 1.45	NA	
	Raseborg s.4 FI	30.93	± 2.61	27.02	± 2.00	NA	
	Raseborg s.5 FI	26.26	± 1.13	25.20	± 1.82	NA	
	E. Finland FI	30.45	± 1.70	24.66	± 2.89	14.46	± 4.34
	St Chély d'a. FR	29.78	± 2.23	27.12	± 3.54	16.35	± 3.75
	Oerrel DE	35.07	± 1.81	25.38	± 1.94	25.17	± 3.17
	Halberstadt DE	34.25	± 1.14	24.58	± 2.02	19.22	± 4.11
	Unterfranken DE	30.79	± 0.78	24.92	± 1.41	21.40	± 5.87
	Klaipeda s.1 LT	30.01	± 2.24	22.11	± 4.50	NA	
	Rognan s.1 NO	26.94	± 1.93	28.56	± 3.52	NA	
	Berkåk s.2 NO	32.31	± 1.81	29.75	± 6.72	NA	
	Åkrestr. s.4 NO	27.07	± 1.91	25.51	± 1.67	NA	
	Kongsb. s.5 NO	30.77	± 0.98	25.20	± 3.73	NA	
	Kongsb. s.9 NO	34.21	± 2.02	28.41	± 2.35	NA	
	Bergen s.7 NO	26.86	± 1.57	24.62	± 3.16	NA	
	Bergen s.8 NO	30.82	± 1.18	23.37	± 0.87	NA	
	Harads s.4 SE	29.62	± 2.29	26.70	± 3.24	NA	
	Borås s.5 SE	30.25	± 1.91	25.71	± 5.16	NA	
	Borås s.6 SE	31.50	± 1.48	26.60	± 2.12	NA	
	Forres s.1 GB	28.85	± 0.93	26.20	± 2.46	NA	
	Munlochy S.2 GB	27.49	± 1.73	19.86	± 2.60	NA	
	Alves GB	31.05	± 1.68	24.73	± 4.51	18.32	± 4.92
	Slovenia SI	34.34	± 2.58	25.01	± 1.72	17.80	± 5.76
	N. Spain ES	26.87	± 1.76	28.38	± 2.40	17.58	± 3.93
	Total mean:	30.66	± 3.20	24.94	± 3.90	18.53	± 5.58
European beech	Haute Saône FR	30.86	± 1.12	32.55	± 2.63	22.86	± 4.08
	Reinhausen DE	14.91	± 9.46	28.39	± 1.58	25.38	± 4.88
	Slovenia SI	26.09	± 1.88	28.35	± 4.79	16.97	± 3.41
	Switzerland CH	25.17	± 2.61	31.91	± 5.80	18.14	± 4.26
	N. Spain ES	30.70	± 3.04	33.48	± 3.22	NA	
	Denmark DK	23.40	± 4.07	27.44	± 3.66	18.01	± 4.18
	Total mean:	24.82	± 6.18	29.67	± 4.56	18.87	± 4.70

In Table 5, Tukey–Kramer HSD comparison of means illustrate that ML_f (*R.p.*) of Norway spruce was highest for material from Hobøl stand 1 (NO), Slovenia, and Breisgau (DE). The lowest ML_f (*R.p.*), were found for the Ribnica stand (SI) and Hobøl stand 3 (NO). Hence, the largest variation in means was found between stands within the same property and municipality in Norway. The highest ML_f (*T.v.*) for Norway spruce was found for Hobøl stand 1 (NO), and lowest for the Ribnica stand (SI), and Rippoldsau (DE). The highest ML_f (TMC) was again for Hobøl stand 1 (NO) and the lowest for Ribnica stand (SI), and Hobøl stand 3 (NO).

Table 5. Norway spruce, Tukey–Kramer HSD (T–K) comparison of mean percent mass loss. Materials not sharing the same letter have statistically significant differences in mean mass loss (ML_f). *R.p.* = *Rhodonia placenta*, *T.v.* = *Trametes versicolor*, TMC = terrestrial microcosm, soft rot test, s. = stand.

	ML_f (*R.p.*)						**ML_f (*T.v.*)**				**ML_f (TMC)**						
Location	**T–K**					**Mean**	**T–K**			**Mean**	**T–K**						**Mean**
Hobøl s.1 NO	A	B	C			31.28	A			27.36	A						30.57
Slovenia SI	A					30.95		B		22.33			C	D			20.35
Breisgau DE	A	B				30.45	A	B		24.71						F	12.78
Hobøl s.2 NO		B	C	D		28.53	A	B		23.88		B	C				22.36
Rippoldsau DE		B	C	D		27.64			C	16.91			C	D	E	F	18.82
Haute Loire FR			C	D		27.50		B		21.85	A	B					24.49
E. Finland FI				D		26.85		B		22.39				D	E		18.05
Ribnica SI					E	24.39			C	16.08					E	F	16.48
Hobøl s.3 NO					E	24.35		B		22.53					E	F	17.04

The main influencing factor of variations in decay performance did not seem to be location, but rather tree or stand level factors. In Table 6, Tukey–Kramer HSD comparison of means illustrate that ML_f (*R.p.*) of Scots pine sapwood varied greatly between locations, the highest ML_f (*R.p.*) was found for material from Nordern Zealand (DK), and the lowest from Raseborg stand 5 in Finland. For ML_f (*T.v.*) the variation between locations was much lower and the significant highest means were found for Kongsberg stand 9 (NO), Berkåk stand 2 (NO), Alves (GB), Raseborg stand 4 (FI), Borås stand 5 (SE), Pudasjärvi stand 1 (FI), Harads stand 4 (SE), Tartu stand 1 (EE), Rognan stand 1 (NO), and Northern Spain.

The material from Denmark and Oerrel (DE) had the significantly highest ML_f (TMC), while Munlochy Stand 2 (GB) had the lowest. As for Norway spruce (Table 5), material from different stands at the same location varied significantly.

The southern European beech material tended to be slightly less resistant against the two tested basidiomycetes and soft rot compared to the more northern material. In Table 7, Tukey–Kramer HSD comparison of means illustrates that for ML_f (*R.p.*) of European beech, three distinct groups were found. The highest ML_f (*R.p.*) was recorded for Haute Saône (FR) and northern Spain, similar ML_f (*R.p.*) for Slovenia, Switzerland and Denmark, and lowest for Reinhausen (DE). The mass loss ML_f (*T.v.*) of European beech from northern Spain, Haute Saône (FR) and Switzerland were higher than the material from Slovenia and Denmark. European beech from Reinhausen (DE) had significantly higher ML_f (TMC) than the material from Slovenia, Switzerland and Denmark.

3.3. Location Level-Moisture

Table 8 provides an overview of mean values for the moisture tests for each of the three wood species at every location included in the dataset. Tables 9–11 provide Tukey–Kramer HSD comparisons of mean values for the moisture tests per wood species between locations.

Location was not the main influencing factor for Norway spruce *LWU*, *VU*, *VR* and *CWU*. According to the Tukey–Kramer HSD comparison of moisture data for Norway spruce between locations (Table 9), *LWU* was highest for the material from Hobøl stand 1 (NO) and Slovenia (SI). For the three stands on the same property in Hobøl (NO), *LWU* was significantly different between the stands. The lowest *LWU* values were found for the two German locations (Rippoldsau and Breisgau), and Eastern Finland. $EMC_{\sim 100\%RH}$ showed no significant variation between stands.

Table 6. Scots pine sapwood, Tukey–Kramer HSD (T–K) comparison of mean percent mass loss. Materials not sharing the same letter have statistically significant differences in mean mass loss (ML_f). *R.p.* = *Rhodonia placenta*, *T.v.* = *Trametes versicolor*, TMC = terrestrial microcosm, soft rot test, NA = not available, s. = stand.

	ML_f (*R.p.*)												ML_f (*T.v.*)				ML_f (TMC)					
Location	**T–K**											**Mean**	**T–K**			**Mean**	**T–K**					**Mean**
N. Zealand DK	A											39.24	A	B	C	23.79	A					26.55
Oerrel DE		B										35.07	A	B		25.38	A	B				25.17
Slovenia SI		B	C									34.34	A	B		25.01			C	D		17.80
Halberstadt DE		B	C	D								34.25	A	B		24.58			C	D		19.22
Kongsb. s.9 NO		B	C	D	E							34.21	A			28.41			NA			
Berkåk s.2 NO		B	C	D	E	F						32.31	A			29.75			NA			
Tartu s.2 EE			C	D	E	F						31.95	A	B	C	23.38			NA			
Borås s.6 SE				D	E	F						31.50	A	B		26.60			NA			
Alves GB					E	F						31.05	A			24.73			C	D		18.32
Raseborg s.4 FI					E	F						30.93	A			27.02			NA			
Bergen s.8 NO				D	E	F	G	H	I	J		30.82	A	B	C	23.37			NA			
Unterfranken DE					E	F						30.79	A	B		24.92		B	C			20.40
Kongsb. s.5 NO					E	F	G					30.77	A	B		25.20			NA			
E. Finland FI						F	G		I			30.45	A	B		24.66					E	14.46
Borås s.5 SE						F	G		I	J		30.25	A			25.71			NA			
Klaipeda s.1 LT						F	G		I	J		30.01		B	C	22.11			NA			
Pudasjärvi s.1 FI						F	G		I	J		29.96	A			26.85			NA			
Heinävesi s.3 FI					E	F	G	H	I	J	K	29.90	A	B		26.80			NA			
St Chély d'a. FR						F	G		I	J		29.78	A			27.12				D	E	16.35
Harads s.4 SE						F	G	H	I	J		29.62	A			26.70			NA			
Forres s.1 GB						F	G	H	I	J	K	28.85	A	B		26.20			NA			
Tartu s.1 EE							G	H	I	J	K	28.51	A			26.16			NA			
Munloc. s.2 GB								H			K	27.49			C	19.86			NA			
Åkrestr. s.4 NO								H	I	J	K	27.07	A	B	C	25.51			NA			
Rognan s.1 NO								H		J	K	26.94	A			28.56			NA			
N. Spain ES											K	26.87	A			28.38		C	D			17.58
Bergen s.7 NO								H		J	K	26.86	A	B	C	24.62			NA			
Raseborg s.5 FI											K	26.26	A	B		25.20			NA			

Table 7. European beech, Tukey–Kramer HSD (T–K) comparison of mean percent mass loss. Materials not sharing the same letter have statistically significant differences in mean mass loss (ML_f). *R.p.* = *Rhodonia placenta*, *T.v.* = *Trametes versicolor*, TMC = terrestrial microcosm, soft rot test, NA = not available, s. = stand.

	ML_f (*R.p.*)		ML_f (*T.v.*)		ML_f (TMC)	
Location	**T–K**	**Mean**	**T–K**	**Mean**	**T–K**	**Mean**
Haute Saône FR	A	30.86	A B	32.55	A	22.86
N. Spain ES	A	30.70	A	33.48	NA	
Slovenia SI	B	26.09	C	28.35	B	16.97
Switzerland CH	B	25.17	A B	31.91	B	18.14
Denmark DK	B	23.40	C	27.44	B	18.01
Reinhausen DE	C	14.91	B C	28.39	A	25.38

In Table 10, Tukey–Kramer HSD comparison of means illustrates that for Scots pine sapwood it was a general tendency between the tests that the Baltic and Nordic Scots pine sapwood material, with the exception of Denmark, tended to group together. For *LWU*, the highest mean was reached by the material from Denmark and Germany, the lowest from Finland and the Baltics. For $W24_{100\%}$ no clear pattern was found for locations/countries, the highest values were found for the material from Norway, Sweden, Scotland, Finland and the Baltics. $W24_{0\%}$ data from one of the Scottish locations together with material from Finland, the Baltics and Sweden formed one group with low $W24_{0\%}$, the Norwegian material grouped in the middle and the remaining materials had statistically similar $W24_{0\%}$. *CWU* generally followed the same trends as *LWU* while no clear pattern between locations was found for $EMC_{\sim 100\%RH}$.

In Table 11, three distinct groups were found using Tukey–Kramer HSD comparison of means for European beech analysed by *LWU*, the highest mean being Reinhausen (DE). Statistically similar means were found for Denmark and Slovenia, and lowest mean for Switzerland. No significant difference was found for *VU*. For *VR* Reinhausen (DE) and Slovenia had the highest values, and Switzerland the lowest. *CWU* was highest for Slovenia and northern Spain, lowest for Reinhausen (DE). The only difference in $EMC_{\sim 100\%RH}$ was found between Slovenia and Switzerland.

3.4. Correlation Matrix Wood—Effect of Density and Annual Ring Width

In order to examine the effect of initial oven-dry density (ρ_0) and annual ring width (ARW), four regression models (Equation (13a–d)) were provided (Table 12).

Model 1 (ρ_0) shows significant coefficient effects of ρ_0 for all decay fungi/wood species combinations. R^2 show that the model explained some of the data variation for *R. placenta* vs. Norway spruce (R^2 = 0.43) and vs. Scots pine sapwood (R^2 = 0.24), and soft rot vs. Norway spruce (R^2 = 0.33), while for *T. versicolor*, none of the variations in the different decay fungi/wood species combinations was explained by the model.

Model 2 (*ARW*) shows significant coefficient effects of annual ring width for: *R. placenta* vs. Norway spruce and Scots pine sapwood, soft rot vs. Norway spruce and European beech. No significant effects were found for *T. versicolor*. R^2 was low, i.e., the variation in the data was not explained, for any of decay fungi/wood species combinations in this model.

Model 3 (ρ_0 + *ARW*) included ρ_0 and annual ring width. ρ_0 was significant for all decay fungi and wood species combinations, while *ARW* was significant for: *R. placenta* vs. Norway spruce, Scots pine sapwood and European beech, *T. versicolor* vs. Scots pine, soft rot vs. European beech. R^2 show that the model explained roughly half of the data variation for *R. placenta* vs. Norway spruce (R^2 = 0.53) and some of the variation for soft rot (R^2 = 0.328).

Model 4 (ρ_0 + *ARW* + $\rho_0 \times$ ARW) included ρ_0, *ARW* plus the ρ_0-*ARW* interactions for the fungus/material combinations. Again, ρ_0 was significant for all decay fungi and wood species combinations, ARW was significant for: *R. placenta* vs. Scots pine sapwood, *T. versicolor* vs. Scots pine sapwood and European beech. The ρ_0-*ARW* interactions were significant for: *R. placenta* vs. Norway spruce and Scots pine sapwood, soft rot vs. Norway spruce, Scots pine sapwood and European beech. R^2 show that the model explained roughly half of the data variation for Norway spruce vs. *R. placenta* vs. (R^2 = 0.54) and some of the variation for soft rot (R^2 = 0.36). For Scots pine sapwood, one-third of the variation was explained by *R. placenta* (R^2 = 0.30).

Table 8. Means and standard deviation from all moisture tests. NA = not available; s. = stand.

	Location	*VU* [%]		*VR* [%]		*LWU* [%]		*CWU* [g/cm^2]		$EMC_{\sim100\%RH}$	
Norway spruce	Rippoldsau DE	13.87	± 3.01	15.02	± 1.05	56.97	± 5.53	0.29	± 0.04	28.45	± 6.44
	Breisgau DE	11.89	± 1.06	14.03	± 1.68	52.72	± 6.07	0.21	± 0.07	27.37	± 2.84
	E. Finland FI	12.28	± 1.71	16.53	± 1.47	53.13	± 7.78	0.29	± 0.05	28.47	± 2.02
	Haute Loire FR	14.08	± 1.28	18.01	± 1.02	63.27	± 7.98	0.22	± 0.05	29.92	± 1.89
	Slovenia SI	13.69	± 2.39	15.75	± 1.81	71.92	± 9.27	0.35	± 0.05	29.40	± 2.59
	Ribnica SI	11.27	± 2.05	15.49	± 0.69	59.49	± 6.66	0.42	± 0.06	29.40	± 0.79
	Hobøl s.1 NO	13.58	± 1.38	17.85	± 1.71	87.45	± 9.18	0.51	± 0.14	30.53	± 2.61
	Hobøl s.2 NO	12.41	± 1.91	17.18	± 1.05	65.68	± 9.74	0.33	± 0.12	29.37	± 1.80
	Hobøl s.3 NO	11.06	± 1.78	16.00	± 1.84	57.74	± 5.01	0.28	± 0.10	28.39	± 3.12
	Total mean:	12.17	± 2.13	16.27	± 1.67	61.31	± 10.71	0.30	± 0.11	28.94	± 2.59
Scots pine sapwood	N. Zealand DK	12.67	± 1.45	16.25	± 0.83	86.68	± 4.61	0.55	± 0.05	30.31	± 1.42
	Tartu s.1 EE	17.49	± 1.25	7.14	± 0.66	53.47	± 2.97	0.14	± 0.03	31.62	± 1.31
	Tartu s.2 EE	18.01	± 0.20	7.92	± 0.70	58.38	± 0.69	0.20	± 0.10	29.64	± 0.47
	Pudasjärvi s.1 FI	18.15	± 0.22	5.95	± 0.72	55.70	± 1.54	0.11	± 0.04	28.21	± 0.18
	Heinävesi s.3 FI	19.69	-	6.84	-	54.77	-	0.14	-	33.75	-
	Raseborg s.4 FI	19.32	± 1.26	9.50	± 0.02	50.28	± 5.52	0.13	± 0.01	41.33	± 2.18
	Raseborg s.5 FI	16.86	± 0.95	7.78	± 0.08	48.20	± 5.36	0.12	± 0.02	30.11	± 0.31
	E. Finland FI	10.26	± 1.77	15.80	± 2.41	49.93	± 5.10	0.23	± 0.07	28.43	± 2.88
	St Chély d'a. FR	12.28	± 1.46	16.00	± 2.48	59.71	± 6.39	0.24	± 0.03	28.07	± 3.79
	Oerrel DE	12.89	± 1.08	16.75	± 3.85	70.34	± 4.53	0.41	± 0.04	28.43	± 5.42
	Halberstadt DE	10.81	± 1.03	17.41	± 2.10	68.60	± 4.74	0.41	± 0.04	30.55	± 3.04
	Unterfranken DE	14.10	± 4.71	16.48	± 3.65	77.65	± 14.38	0.48	± 0.06	30.52	± 6.32
	Klaipeda s.1 LT	17.80	± 0.58	6.57	± 1.52	53.16	± 3.67	0.15	± 0.02	28.86	± 0.86
	Rognan s.1 NO	NA		NA		NA		NA		NA	
	Berkåk s.2 NO	NA		NA		NA		NA		NA	
	Åkrestr. s.4 NO	20.62	-	14.31	-	51.71	-	NA		37.90	-
	Kongsb. s.5 NO	21.19	± 2.20	14.55	± 4.27	67.68	± 17.26	0.14	± 0.06	34.64	± 6.24
	Kongsb. s.9 NO	21.58	-	8.32	-	65.00	-	0.14	-	25.52	-
	Bergen s.7 NO	20.98	-	7.26	-	54.82	-	0.18	-	29.60	-
	Bergen s.8 NO	21.30	-	8.36	-	57.84	-	0.11	-	29.51	-
	Harads s.4 SE	20,15	± 0.53	5.26	± 0.89	56.84	± 2.30	0.14	± 0.03	30.52	± 1.28
	Borås s.5 SE	17.94	± 0.82	6.04	± 1.07	56.18	± 2.41	0.13	± 0.01	28.50	± 0.64
	Borås s.6 SE	18.29	± 0.08	6.89	± 0.72	56.84	± 4.54	0.15	± 0.01	28.80	± 0.41
	Forres s.1 GB	19.64	± 0.21	8.48	± 0.83	61.89	± 0.48	0.13	± 0.04	33.54	± 0.83
	Munloc. s.2 GB	18.06	± 1.30	8.13	± 4.74	52.80	± 4.55	0.12	± 0.05	34.13	± 5.62
	Alves GB	11.84	± 1.76	15.48	± 0.90	64.49	± 3.67	0.31	± 0.08	29.52	± 1.47
	Slovenia SI	11.93	± 2.16	15.30	± 0.76	67.14	± 9.66	0.45	± 0.06	28.95	± 0.75
	N. Spain ES	10.99	± 1.49	15.68	± 1.70	64.08	± 4.21	0.46	± 0.15	29.72	± 2.55
	Total mean:	13.97	± 3.93	13.13	± 4.54	60.55	± 11.04	0.29	± 0.14	29.90	± 3.56
European beech	Haute Saône FR	10.89 ± 1.22		17.59	± 0.95	57.72	± 3.36	0.19	± 0.03	30.54	± 1.11
	Reinhausen DE	11.70	± 3.90	16.83	± 0.77	64.90	± 1.64	0.15	± 0.04	30.74	± 1.45
	Slovenia SI	9.54	± 1.53	16.27	± 1.52	54.21	± 3.28	0.31	± 0.05	31.02	± 2.40
	Switzerland CH	10.78	± 2.06	15.08	± 0.88	46.51	± 6.24	0.19	± 0.03	29.07	± 1.55
	N. Spain ES	NA		NA		NA		0.27	± 0.06	NA	
	Denmark DK	10.56	± 2.84	15.82	± 0.99	55.32	± 6.76	0.20	± 0.03	29.83	± 1.89
	Total mean:	10.48	± 2.39	15.99	± 1.33	53.70	± 7.39	0.21	± 0.06	30.10	± 2.00

Table 9. Norway spruce, Tukey–Kramer HSD (T–K) comparison of mean moisture data. Materials not sharing the same letter have statistically significant differences in mean moisture parameters. Moisture data from Berkåk s.2 (NO) and Rognan s.1 (NO) not available; s. = stand.

	LWU						*VU*					*VR*					*CWU*					*EMC~100%RH*	
Location	**T-K**					**Mean**	**T–K**				**Mean**	**T–K**				**Mean**	**T–K**				**Mean**	**T–K**	**Mean**
Hobøl s.1 NO	A					87.45	A	B			13.58	A				17.85	A				0.51	A	30.52
Slovenia SI		B				71.92	A				13.69		B	C		15.75		B	C		0.35	A	29.40
Breisgau DE			C			65.68	A	B	C		12.41	A				17.18		B			0.33	A	29.37
Hobøl s.2 NO		B	C	D		63.27	A	B			14.08	A				18.01			C	D	0.22	A	29.92
Rippoldsau DE				D		59.49			C	D	11.27			C	D	15.49	A	B			0.42	A	29.40
Haute Loire FR				D		57.74				D	11.06		B	C		16.00		B	C	D	0.28	A	28.39
E. Finland FI				D	E	56.97	A	B			13.87		B	C	D	15.02		B	C	D	0.29	A	28.45
Ribnica SI					E	53.13		B	C		12.28	A	B			16.53		B	C	D	0.29	A	28.47
Hobøl s.3 NO				D	E	52.72	A	B	C	D	11.89				D	14.03				D	0.21	A	27.37

Table 10. Scots pine sapwood, Tukey–Kramer HSD (T–K) comparison of mean moisture data. Materials not sharing the same letter have statistically significant differences in mean moisture parameter. Material collected by Zimmer et al. [21], marked with *, was merged at country level, since only very few measurements were taken per stand; s. = stand.

	LWU									*VU*						*VR*				*CWU*							*EMC~100%RH*				
Location	**T-K**								**Mean**	**T–K**					**Mean**	**T–K**			**Mean**	**T–K**						**Mean**	**T–K**				**Mean**
N. Zealand DK	A								86.68			C	D		12.67	A			16.25	A						0.55	A	B	C	D	30.31
Unterfrank. DE	A	B							77.65			C			14.10	A			16.48	A	B					0.48	A	B	C	D	30.52
Oerrel DE		B	C						70.34			C	D		12.89	A			16.75		B					0.41		B	C	D	28.43
Halberstadt DE		B	C	D					68.60				D	E	10.81	A			17.41		B					0.41	A	B	C	D	30.55
Slovenia SI			C	D					67.14			C	D		11.93	A			15.30		B					0.45			C	D	28.95
Alves GB			C	D					64.49				D		11.84	A			15.48			C				0.31		B	C	D	29.52
N. Spain ES			C	D	E				64.08				D	E	10.99	A			15.68	A	B					0.46	A	B	C	D	29.72
Norway *			C	D	E	F			61.77	A					21.15		B		11.70				D	E	F	0.14	A	B	C		32.35
St Chély FR				D	E	F	G		59.71			C	D	E	12.28	A			16.00			C	D	E		0.24			C	D	28.07
Sweden *					E	F	G		56.59		B				18.86			C	5.96						F	0.14		B	C	D	29.33
Scotland GB *						F	G	H	55.07		B				18.46			C	8.22						F	0.12	A				33.98
Baltics *							G	H	53.96		B				17.73			C	6.94					E	F	0.15		B	C	D	29.88
Finland *							G	H	52.35		B				18.31			C	7.41						F	0.12	A	B			32.66
E. Finland FI								H	49.93					E	10.26	A			15.80				D			0.23				D	28.43

Table 11. European beech, Tukey–Kramer HSD (T–K) comparison of mean moisture data. Materials not sharing the same letter have statistically significant differences in mean moisture parameters. NA = not available.

	LWU		*VU*		$W24_{0\%RH}$		*CWU*		$EMC_{\sim 100\%RH}$	
Location	**T–K**	**Mean**	**T–K**	**Mean**	**T–K**	**Mean**	**T–K**	**Mean**	**T–K**	**Mean**
Reinhausen DE	A	64.90	A	11.70	A	16.83	C	0.15	A B	30.74
Haute Saône FR	B	57.72	A	10.89	A	17.59	B C	0.19	A B	30.54
Denmark DK	B	55.32	A	10.56	B C	15.82	B	0.20	A B	29.83
Slovenia SI	B	54.21	A	9.54	B	16.27	A	0.31	A	31.02
Switzerland CH	C	46.51	A	10.78	C	15.08	B C	0.19	B	29.07
N. Spain ES	NA		NA		NA		A	0.27	NA	

Table 12. Overview on model statistics, giving the coefficient of determination for four different models Model 1–Model 4, for Norway spruce, European beech and Scots pine sapwood and the respective decay fungi *Rhodonia placenta* (*R.p.*), *Trametes versicolor* (*T.v.*) and TMC. For β_0 (population intercept) and β_i (population slope coefficient), the respective *p*-values are noted, where a * indicates statistical significance. ρ_0 = initial oven-dry density, *ARW* = annual ring width.

	Model 1 (ρ_0)				**Model 2 (*ARW*)**				
			ρ_0				*ARW*		
	R^2	β_0	β_1		R^2	β_0	β_1		
Norway spruce									
R.p.	0.439	<0.0001 *	<0.0001 *		0.093	<0.0001 *	<0.0001 *		
T.v.	0.040	<0.0001 *	0.0052 *		0.0001	<0.0001 *	0.8774		
TMC	0.325	<0.0001 *	<0.0001 *		0.014	<0.0001 *	0.0218 *		
Scots pine sapwood									
R.p.	0.236	<0.0001 *	<0.0001 *		0.085	<0.0001 *	<0.0001 *		
T.v.	0.037	<0.0001 *	<0.0001 *		0.004	<0.0001 *	0.1665		
TMC	0.171	<0.0001 *	<0.0001 *		0.005	<0.0001 *	0.1780		
European beech									
R.p.	0.030	<0.0001 *	0.0459 *		0.026	<0.0001 *	0.067		
T.v.	0.097	<0.0001 *	0.0003 *		0.0003	<0.0001 *	0.8415		
TMC	0.220	<0.0001 *	<0.0001 *		0.013	<0.0001 *	0.0687		
	Model 3 (ρ_0 + *ARW*)				**Model 4 (ρ_0 + *ARW* + ρ_0 x *ARW*)**				
			ρ_0	*ARW*			ρ_0	*ARW*	ρ_0 x *ARW*
	R^2	β_0	β_1	β_2	R^2	β_0	β_1	β_2	β_3
Norway spruce									
R.p.	0.532	<0.0001 *	<0.0001 *	<0.0001 *	0.544	<0.0001 *	<0.0001 *	0.0979	0.0235 *
T.v.	0.078	<0.0001 *	<0.0001 *	0.0058	0.078	<0.0001 *	0.0006 *	0.0956	0.7714
TMC	0.328	<0.0001 *	<0.0001 *	0.1827	0.362	<0.0001 *	<0.0001 *	0.1297	<0.0001 *
Scots pine sapwood									
R.p.	0.263	<0.0001 *	<0.0001 *	<0.0001 *	0.300	<0.0001 *	<0.0001 *	<0.0001 *	<0.0001 *
T.v.	0.075	<0.0001 *	<0.0001 *	<0.0001 *	0.079	<0.0001 *	<0.0001 *	<0.0001 *	0.1534
TMC	0.173	<0.0001 *	<0.0001 *	0.3784	0.203	<0.0001 *	<0.0001 *	0.1572	<0.0001 *
European beech									
R.p.	0.059	<0.0001 *	0.0342 *	0.0498 *	0.059	<0.0001 *	0.0395 *	0.0601	0.8178
T.v.	0.098	<0.0001 *	<0.0003 *	0.8762	0.123	<0.0001 *	<0.0011 *	0.6042	0.0543
TMC	0.235	<0.0001 *	<0.0001 *	0.0238 *	0.241	<0.0001 *	<0.0001 *	0.0278	0.1897

This model approach illustrates that ρ_0 and the combination of ρ_0 and *ARW* is an influencing factor for *R. placenta* decay of the softwoods. For soft rot, the effect of ρ_0 and the combination of ρ_0 and *ARW* was strongest for Norway spruce. With the model used here, no effect of ρ_0 and/or *ARW* was found for *T. versicolor*. For practical purposes, this implies that especially for decay tests with *R. placenta* the recommendations in standards regarding density and annual ring width are of great importance.

Stirling et al. [24] noted that "Greater attention should be given to characterisation and reporting of material quality, e.g., density, annual year ring width, and ideally also water sorption properties of individual test specimens". This study confirms this. In order to ensure reproducibility and comparability of experiments it is recommended to: (1) follow the specifications for annual ring width in standards, and (2) preferably report the ring width and density for individual specimens. Sandberg and Salin [25] performed adsorption tests on Norway spruce and found differences in liquid water absorption between sapwood and heartwood as well as between trees from different growth conditions. According to Stirling et al. [24] species with the greatest absorption and retention of water decayed most rapidly. Latewood content and growth conditions influenced the treatability of Scots pine sapwood significantly [21] and in this context, latewood content was shown to be more important than density due to the open pathways provided by the unaspirated bordered pits in the dried wood. These pathways could also be beneficial in the initial wetting of the wood prior to fungal infestation. Position in the stem, tree origin, and latewood content are therefore factors, which could add to some of the unexplained variations in the models.

4. Conclusions

The variation of the examined durability and moisture performance indicators was surprisingly low within and between the three reference wood species usually considered for wood durability testing in Europe. Therefore, in Part 2 of this series [18], the obtained conversion factors will further be used to utilize existing durability tests for validating and optimizing the 'Meyer-Veltrup model' for material-resistance [7]. Additionally, Part 3 of this publication [19] will survey wood durability test data, utilize them for implementation in a material resistance model and generate a database for service life prediction of wood products in above and in-ground situations.

Nevertheless, annual ring width and oven-dry density turned out to be decisive parameters and can explain the variation of reference species' properties to a great extent. Hence, carefully selecting wood material from reference species with respect to these parameters is recommended to assure high accuracy and reproducibility of both durability and moisture performance tests.

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Data Availability Statement: All mean values, standard deviations and number of replicates per wood material, fungi and location for the dataset are presented in this paper. The entire set of raw data presented in this study is available on request from the corresponding author.

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