IRG/WP 10-20439

THE INTERNATIONAL RESEARCH GROUP ON WOOD PROTECTION

Section 2 Test methodology and assessment

Service life prediction of wooden components – Part 1:

Determination of dose-response functions for above ground decay

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Paper prepared for the 41st Annual Meeting
Biarritz, France
9-13 May 2010

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Service life prediction of wooden components – Part 1: Determination of dose-response functions for above ground decay

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ABSTRACT

Scots pine sapwood (*Pinus sylvestris* L.) and Douglas fir heartwood (*Pseudotsuga menziesii* Franco) specimens were exposed in double layer field trials at 24 different European test sites under different exposure conditions (in total 28 test sets). The material climate in terms of wood moisture content (MC) and wood temperature was automatically recorded over a period of up to eight years and compared with the progress of decay. The final results of the study are presented within this paper.
Significant differences among the test sites were observed regarding the time lag between the start of exposure and the onset of decay as well as the progress of decay. The overall aim of this study was to establish dose-response relationships between climate factors and decay as a basis for service life prediction of wooden components. The use of the combined material climatic parameters MC and wood temperature led to a feasible dose-response function and turned out to be a useful basis for service life prediction.
How to apply this approach for estimating the expected lifetime of wooden components under various exposure conditions will be shown in part 2 of this series.

Keywords: double layer test, dose-time function, field test, material climate, test site, wood moisture content, wood temperature

1. INTRODUCTION

The service life of timber in outdoor applications is influenced by numerous factors, both wood-inherent properties and environmental factors. Site-specific climate has a major influence on wood decay and needs therefore to be considered for service life prediction of wooden components (Brischke and Rapp 2008). A number of different approaches have been taken to establish climate based indices for estimating the site-specific decay potential (Scheffer 1971; Beesley et al. 1983; Creemers et al. 2002; Grinda and Carey 2004), but all failed to establish a sufficiently strong correlation between macro climatic data and decay that would allow them to be used for reliable service life prediction (De Groot 1982; Norén 2001; Brischke et al. 2008b).

The influence of macro- and microclimates on decay should be especially apparent with "wood moisture content" (MC) and "wood temperature" (Brischke and Rapp 2008). The overall aim of this study was therefore to establish dose-response functions for wood decay with wood MC and temperature. Wood MC, wood temperature, and decay progress were monitored for up to eight years in above ground samples at 28 different exposure sites in Europe and used to establish links between dose and response.

2. EXPERIMENTAL METHODS

2.1 Field tests

Field test specimens cut from Scots pine sapwood (*Pinus sylvestris* L.) and Douglas fir heartwood (*Pseudotsuga menziesii* Franco) were monitored in terms of MC, wood temperature, and the progress of fungal decay up to a period of seven years. The specimens (500x50x25 mm^3), according to EN 252 (1989), were exposed horizontally in double layer test rigs (Rapp and Augusta 2004) producing a decay risk corresponding to European Use Class 3 (EN 335-1, 2006). The upper layer was displaced laterally by 25 mm with respect to the lower layer. The lower layer consisted of seven pine sapwood specimens and six Douglas fir specimens; the upper layer consisted of six pine sapwood specimens and five Douglas fir specimens. The specimens were supported at the cut ends by beams of CCB-impregnated pine sapwood, separated with bitumen foil from the preservative-treated supports. The whole test set-up formed a closed deck (73x65x21 cm^3). To avoid the growth of grass it was placed on paved ground or horticultural foil.

The test rigs were exposed at 24 sites in Europe, which were selected to provide a range of climate regimes (one test rig at each site/for each exposure). Climate data at all sites were available from official weather stations, where measurements of daily precipitation and average daily temperature were recorded. The characteristic data for the test sites are listed in Table 1. Additionally, a second set of specimens at some sites was artificially shaded. “Shade sets” were put in plywood boxes (30x90x90 cm^3) covered with fully water-permeable textile sheets, which were transmitting only 10% of the incident sunlight. At the Federal Research Centre for Forestry and Forest Products (BFH) in Hamburg sets were exposed in a tropical greenhouse during the winter (Oct 15th – May 15th), and the whole year (Table 1). The exposure in shade boxes and in the tropical greenhouse was carried out to provoke changes in terms of the microclimate and to promote the conditions for decay.

2.2 Decay assessment

The specimens were evaluated yearly by using the so-called “pick-test” and rating the extent and distribution of decay according to EN 252 (1989) as: 0 (sound), 1 (slight attack), 2 (moderate attack), 3 (severe attack), or 4 (failure).

2.3 Automated recordings of wood moisture content (MC) and wood temperature

The MC of three pine sapwood and three Douglas fir heartwood samples in the bottom layer of each test set was recorded once a day. The measurement system applied in this study was described in an earlier publication (Brischke et al. 2008a) and can be summarized in brief as follows: Electrodes of polyamide coated stainless steel cables were conductively glued in the specimens. The electrodes were connected to a small data logger (Materialfox Mini, Scanntronik Mugrauer GmbH, Zorneding, Germany), which recorded the electrical resistance of the wood. The data loggers were calibrated in a range between 12% and 50% MC (Brischke et al. 2008a). Measurements above fibre saturation were increasingly inaccurate, but still indicated a tendency within the calibration range. Minimum and maximum temperature below the bottom layer of each test set were recorded daily using Thermofox Mini data logger (Scanntronik Mugrauer GmbH, Zorneding, Germany) and used to calculate the average daily temperature.

Table 1: Characteristic data of exposure sites

Test site and exposure	Country code	Height above sea level [m]	Average air temperature [°C]		Sum of precipitation [mm]		Begin of exposure	Last evaluation
Hamburg sun/shade	D	35	10.6	1)	874	1)	07/2000	06/2008
Greenhouse	D	35	21.6	4)	6257	3)	07/2000	06/2008
Greenhouse winter	D	35	18.6	4)	4092	3)4)	07/2000	06/2008
Reulbach sun/shade	D	620	7.5	2)	820	1)	07/2000	09/2008
Stuttgart sun/shade	D	459	9.9	2)	741	1)	07/2000	09/2008
Freiburg sun/shade	D	302	12.1	1)	911	1)	07/2000	09/2008
Oberrottweil	D	221	11.7	1)	731	1)	12/2000	09/2008
Feldberg	D	1496	4.3	4)	1588	4)	12/2000	09/2008
Bühlertal	D	465	9.8	5)	1664	5)	12/2000	09/2008
Hornisgrinde	D	1131	6.0	5)	2030	5)	12/2000	09/2008
Hinterzarten	D	887	7.0	5)	1586	5)	12/2000	09/2008
Schömberg	D	635	8.0	4)	954	1)	12/2000	09/2008
Heilbronn/Heidelberg10)	D	173/111	11.2/11.7	10)	769/679	10)	12/2000	09/2008
Dobel	D	706	9.0	9)	1473	9)	12/2000	09/2007
St. Märgen	D	908	8.2	1)	1834	1)	12/2000	09/2008
Uppsala	S	7	6.8	5)	579	5)	05/2001	09/2008
Ljubljana	SLO	299	11.3	1)	1330	1)	04/2001	11/2008
Zagreb	HRO	123	10.7	4)	910	4)	08/2002	10/2008
London	GB	62	11.9	8)	649	8)	07/2002	11/2008
Garston	GB	90	10.7	7)	515	7)	07/2002	09/2008
Portsmouth	GB	1	11.6	6)	667	6)	04/2001	09/2008
Ghent	B	9	10.9	1)	758	1)	08/2002	09/2008
Bordeaux	F	4	14.0	5)	798	5)	01/2001	09/2008
Oslo	N	124	7.5	11)	871	11)	08/2004	09/2008

1)average of 2000-2005
2)average of 2001-2005
3)equivalent to a spraying of 120l per week
4)average of 2000-2004
5)average of 2000-2006
6)average of 2002-2006
7)average of Jul 2002-Jun 2006
8)average of 2002-2005
9)average of 2000-2003
10)site was changed in 10/2003 from Heilbronn to Heidelberg, average of 2000-2003, and 2004-2006 respectively
11)average of Oct 2004-Sep 2008

3. RESULTS AND DISCUSSION

3.1 Relationship between time of exposure and decay

There was high variation between decay progress at the different exposure sites for both, Scots pine sapwood (Fig. 1) and Douglas fir heartwood (Fig. 2). In Ljubljana decay was most rapid and pine sapwood specimens failed completely after 4 years of exposure. In contrast, first decay was observed after 3.3 years on pine at the Uppsala site, where decay was least rapid. Thus, test site influences decay. The time lags between begin of exposure and the first detection of visible decay ranged between 0.4 years in Greenhouse and more than 4.0 years in London (Table 2). Numerous inhibitory effects on fungal activity, e.g. competition and antagonism between species, inhibitory extractives and initially low permeability of the wood, potentially cause these time lags (Brischke and Rapp 2008). The progress of decay, especially after the onset of visible decay, is presumably determined by temperature and MC inside the wood, and should therefore be seen as the main parameters for establishing a dose-response function. There may also be interactions between incipient decay inhibition and the moisture/temperature induced dose.

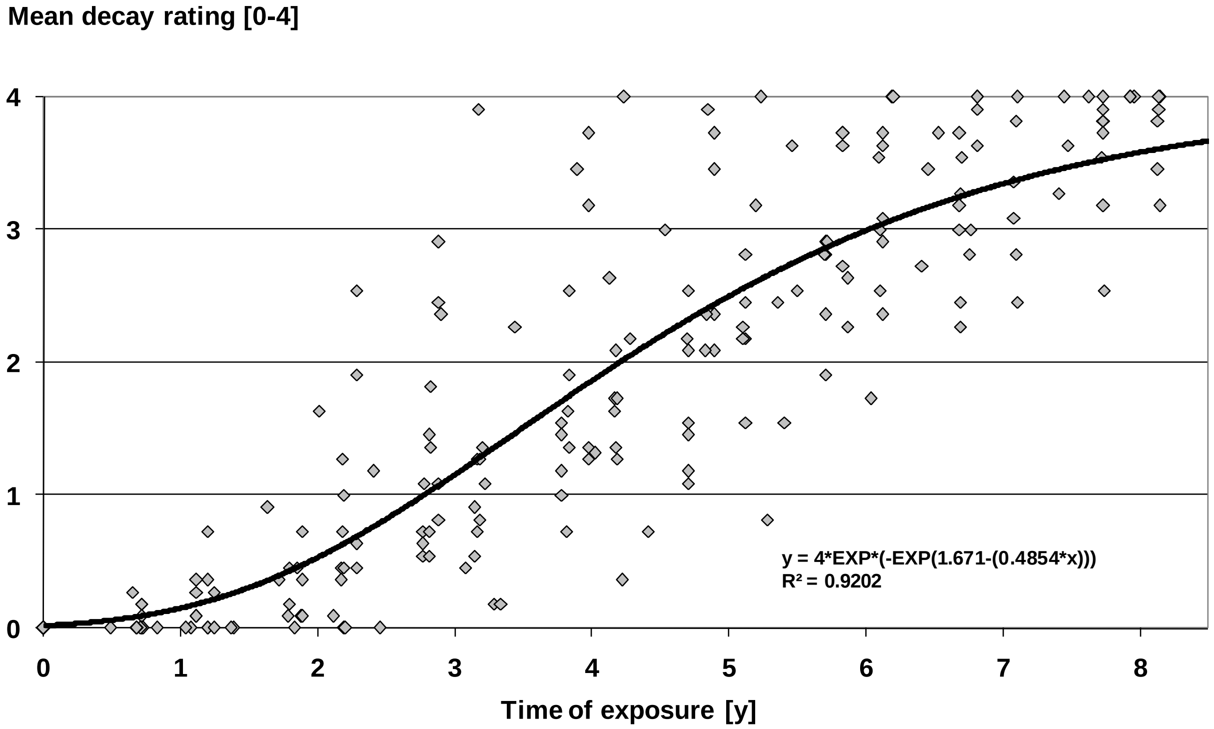

Figure 1: Relationship between the time of exposure and the mean decay rating according to EN 252 (1989) of Scots pine sapwood specimens exposed at 28 different exposure sites (each dot represents the mean decay rating at one exposure site at a certain time of exposure; black line: Gompertz smoothing function).

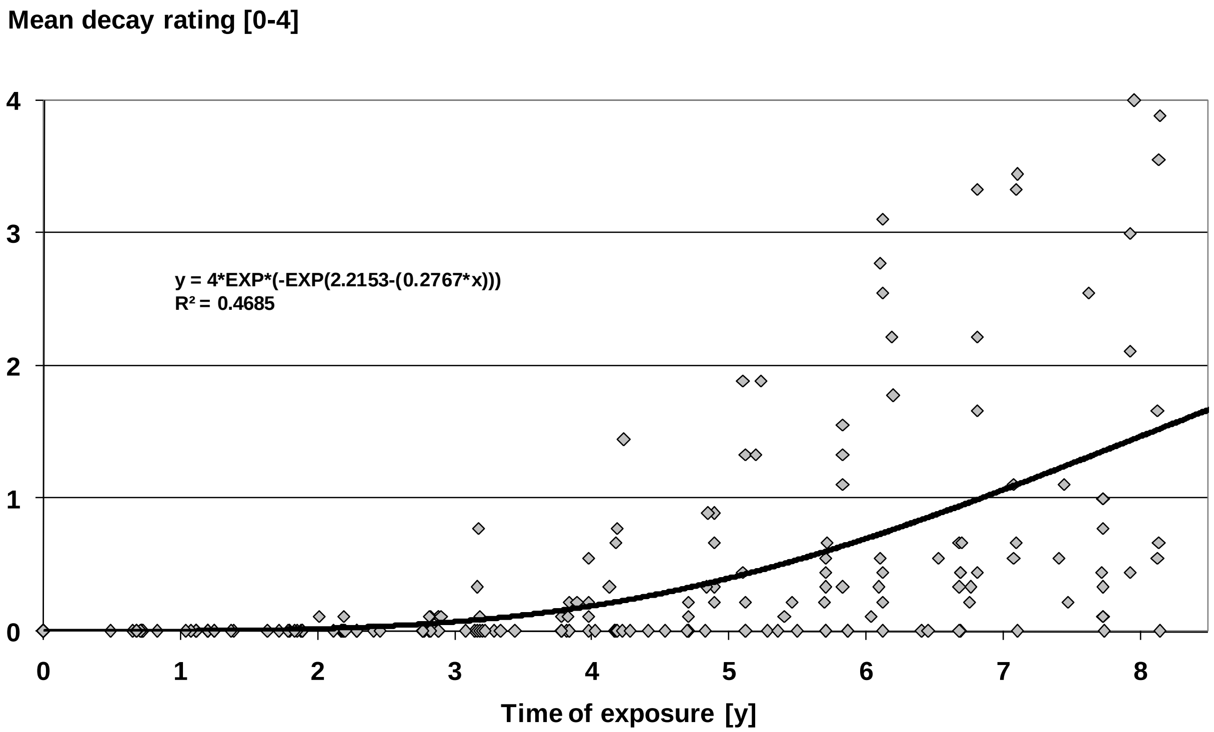

Figure 2: Relationship between the time of exposure and the mean decay rating according to EN 252 (1989) of Douglas fir heartwood specimens exposed at 28 different exposure sites (each dot represents the mean decay rating at one exposure site at a certain time of exposure; black line: Gompertz smoothing function).

Table 2: Mean time lags (exposure time before first incidence of decay) for Scots pine sapwood and Douglas fir heartwood at the different exposure sites.

Test site and exposure	**Mean time lag [a]**	
	Pine sapwood	**Douglas fir heartwood**
Hamburg sun	2.2	4.3
Hamburg shade	1.7	4.8
Greenhouse	0.4	> 7.1
Greenhouse winter	0.9	4.7
Reulbach sun	2.1	> 6.9
Reulbach shade	1.7	> 6.1
Stuttgart sun	1.8	> 8.1
Stuttgart shade	1.2	4.3
Freiburg sun	1.6	> 6.2
Freiburg shade	0.8	3.8
Oberrottweil	2.4	> 7.4
Feldberg	1.9	> 7.7
Bühlertal	1.2	> 5.4
Hornisgrinde	1.9	> 7.6
Hinterzarten	1.7	> 6.2
Schömberg	2.2	> 7.0
Heilbronn/Heidelberg	1.5	> 6.2
Dobel	2.5	> 6.6
St. Märgen	1.7	> 6.4
Uppsala	3.8	> 6.6
Ljubljana	1.3	> 4.2
Zagreb	1.5	> 4.1
London	4.0	> 6.4
Garston	2.1	> 4.6
Portsmouth	0.7	> 5.9
Ghent	2.4	> 6.0
Bordeaux	n.a.	n.a.
Oslo	> 3.2	> 4.0

n.a. = not available

3.2 MC and wood temperature based dose-response functions

The average daily wood temperature and MC were used to estimate the daily dose in terms of a decay hazard. The total daily dose (d), which impacts on the wood, was therefore assumed to be the product of a moisture induced component d_{MC} and a temperature induced component d_T. Starting from literature data, the cardinal points of both parameters, wood temperature and MC, for fungal growth and decay activity were sought and used to set up polynomial base functions for both dose components (cf. Fig. 3).

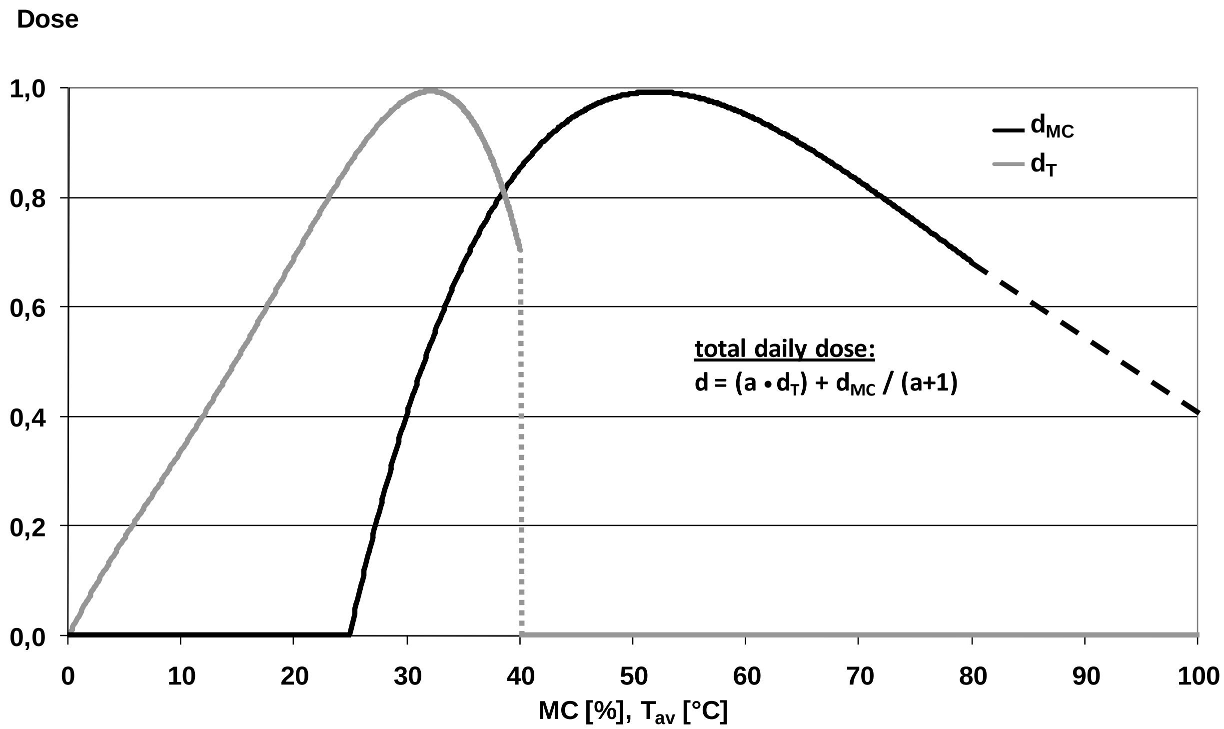

Figure 3: Relationship between MC and daily moisture induced dose d_{MC}, and between average wood temperature T_{av} and daily temperature induced dose d_T respectively. Dashed black line: MC>80% did not occur; therefore the curve progression is uncertain.

Because of the diversity of fungal species potentially occurring in the field, cardinal ranges can be found, rather than exact cardinal points for MC and temperature. As a minimum the MC for fungal decay needs to be above fibre saturation (Schmidt 2006), otherwise the enzymes released by the fungus, which are responsible for the decomposition of the cell-wall components, will not be transported and are therefore inactive. Thus the moisture minimum for fungal growth is around 26 to 30%, whereas the optimum for many relevant basidiomycetes ranges between 35% and 70% (Rypáĉek 1966; Huckfeldt et al. 2005). The upper moisture limit for most wood decay basidiomycetes is 90% MC (Bavendamm 1974), although some fungi have higher moisture maxima, e.g. *Gloeophyllum abietinum*, different blue stain fungi, and red-streakiness causing fungi (Schuhmacher and Schulz 1992; Schmidt 2006).

In general, the minimum temperature for fungal growth is 0°C, because no liquid water is available in hyphae, provided that the freezing point of water is not lowered by a modified chemical composition of the fungal protoplasm or the wood (Jennings and Lysek 1999). The optimum temperatures for fungal activity are strongly dependent on the species, but range frequently between 20 and 40°C (e.g. Schmidt 2006). The optimum for fungal decay however can be different, i.e. lower, from the optimum for fungal growth. The maximum for mycelial growth and wood decay by most wood fungi is often 40 to 50°C (Rypáĉek 1966; Schmidt 2006).

The mean values of the cardinal points as described above were used to formulate a base function for both dose components. Minima and maxima were set as dose = 0, the optima as dose = 1. Furthermore an approximately linear course progression was assumed, with respect to the "reaction speed-temperature rule" between minimum and maximum temperature (Schmidt 2006), whereby enzyme activity is increased by two to four times with each 10°C increase in temperature.

The daily dose was accumulated and correlated with the corresponding decay ratings for the different exposure intervals and test sites. The sigmoid course of the dose-response relationship was fitted with a Gompertz-function (*cf.* Fig. 4). Based on the method of least squares for the dose-response function, all variables of the daily dose functions (d_{MC} and d_T) were optimized using MS Excel Solver. The following side conditions were considered: the total daily dose of days with a maximum temperature above 40°C, with a minimum temperature below –1°C, or with a MC below 25% was set as 0.

The computed optimization revealed the following fifth-degree polynomial for the MC induced (Eq. 1), and a fourth-degree polynomial for the temperature induced daily dose (Eq. 2), as shown in Fig. 3:

$$d_{MC} = 6.75 \bullet 10^{-10}\, MC^5 - 3.50 \bullet 10^{-7}\, MC^4 + 7.18 \bullet 10^{-5}\, MC^3 - 7.22 \bullet 10^{-3}\, MC^2 + 0.34MC - 4.98$$
$$; \text{if } MC \geq 25\% \quad (1)$$

$$d_T = 1.8 \bullet 10^{-6}\, T^4 + 9.57 \bullet 10^{-5}\, T^3 - 1.55 \bullet 10^{-3}\, T^2 + 4.17 \bullet 10^{-2}\, T$$
$$; \text{if } T_{min} > -1°C \text{ and } T_{max} < 40°C \quad (2)$$

d_{MC} = MC induced daily dose

d_T = temperature induced daily dose

MC = daily moisture content

T = daily average wood temperature

T_{min}= daily minimum temperature

T_{max}= daily maximum temperature

To consider the differently severe impact of MC and temperature on decay the weighting factor a was added to calculate the daily dose as follows:

Daily dose d:

$$d = ((a \bullet d_T) + d_{MC}) / (a + 1)$$
$$; \text{if } d_T > 0 \text{ and } d_{MC} > 0 \quad (3)$$

a = 3,2 (weighting factor of temperature induced daily dose component d_T)

The MC and temperature induced dose correlated well with fungal decay as response (Fig. 4 +5; R^2=0.9432), whereby nearly identical dose-response functions were obtained for both wood species. The statistical spread could be reduced significantly compared to considering exposure time only (cf. Fig. 1 + 2).

The remaining variation can be attributed to a few sites only (e.g. Ljubljana, Zagreb), where less dose led already to higher response in terms of higher decay ratings. As can be seen from Tab. 3 white rot and soft rot were predominant at most of the sites especially on pine sapwood. Most frequently brown rot was found on pine sapwood at the sites Ljubljana, Freiburg shade, and Bordeaux, whereby only in Ljubljana the decay response was above average. Thus, a general rule, that brown rot caused higher decay rates for equal doses, could not be established.

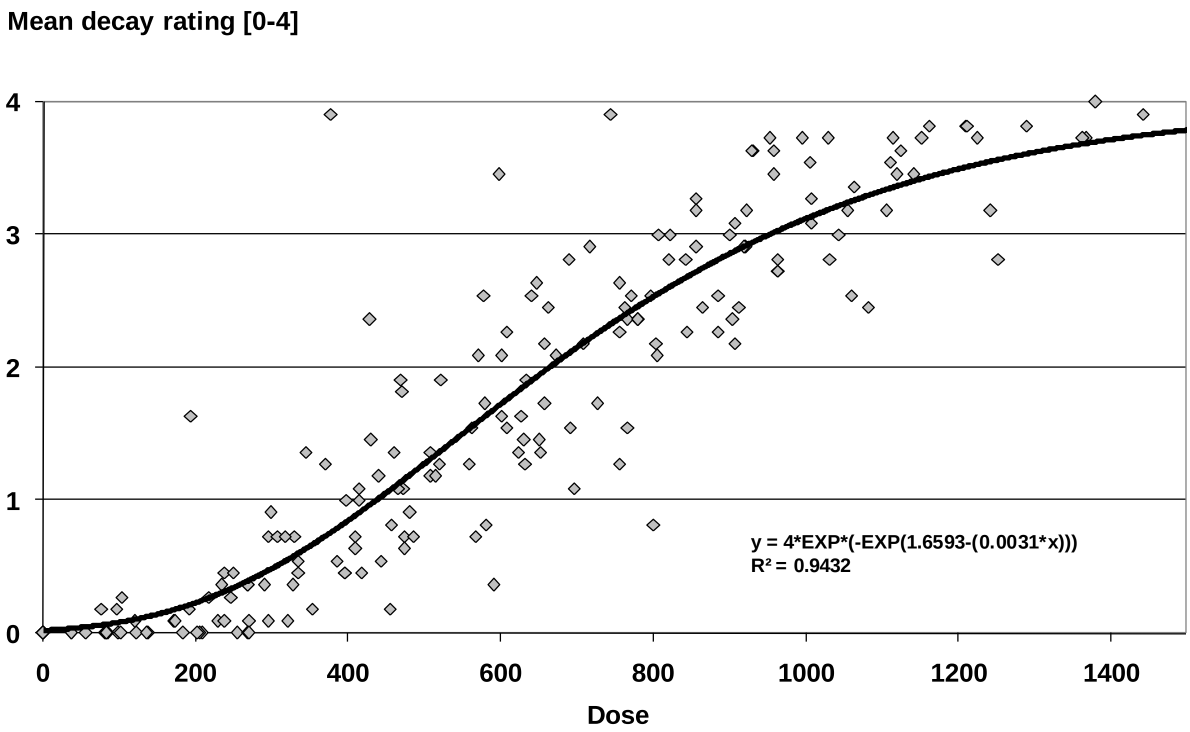

Figure 4: Relationship between the dose and the mean decay rating according to EN 252 (1989) of Pine sapwood specimens exposed at 28 different field test sites (each dot represents the mean decay rating at one exposure site at a certain time of exposure; black line: Gompertz smoothing function).

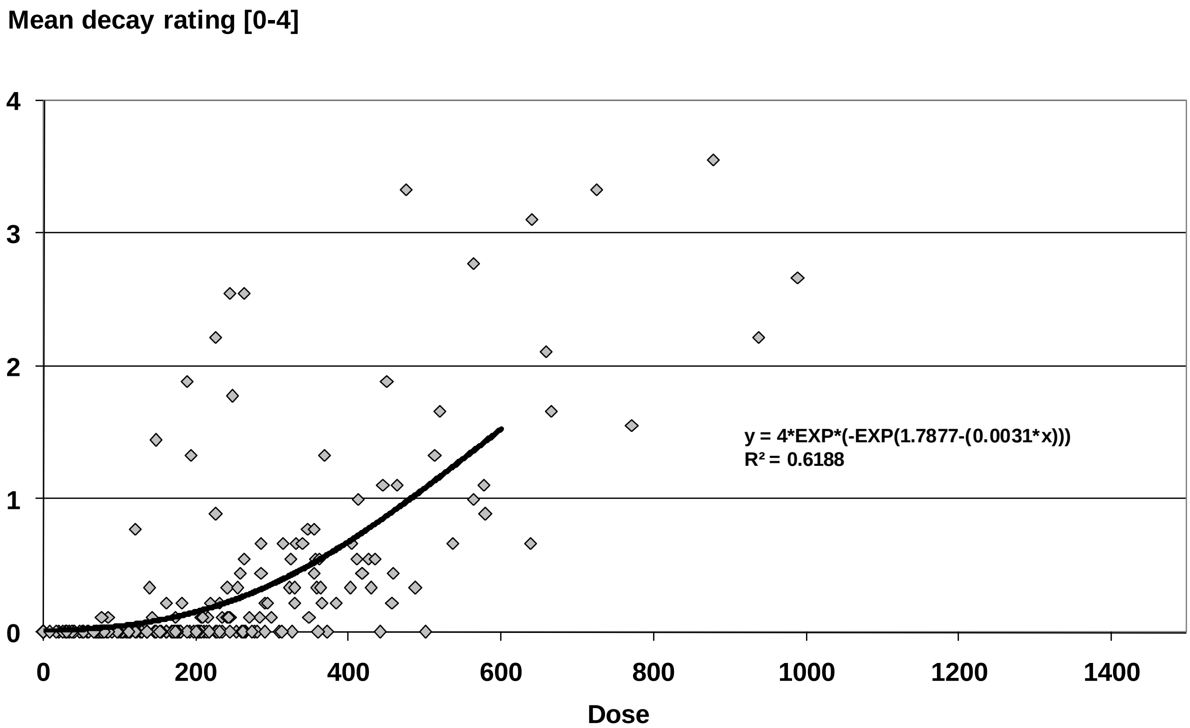

Figure 5: Relationship between the dose and the mean decay rating according to EN 252 (1989) of Douglas fir heartwood specimens exposed at 28 different field test sites (each dot represents the mean decay rating at one exposure site at a certain time of exposure; black line: Gompertz smoothing function).

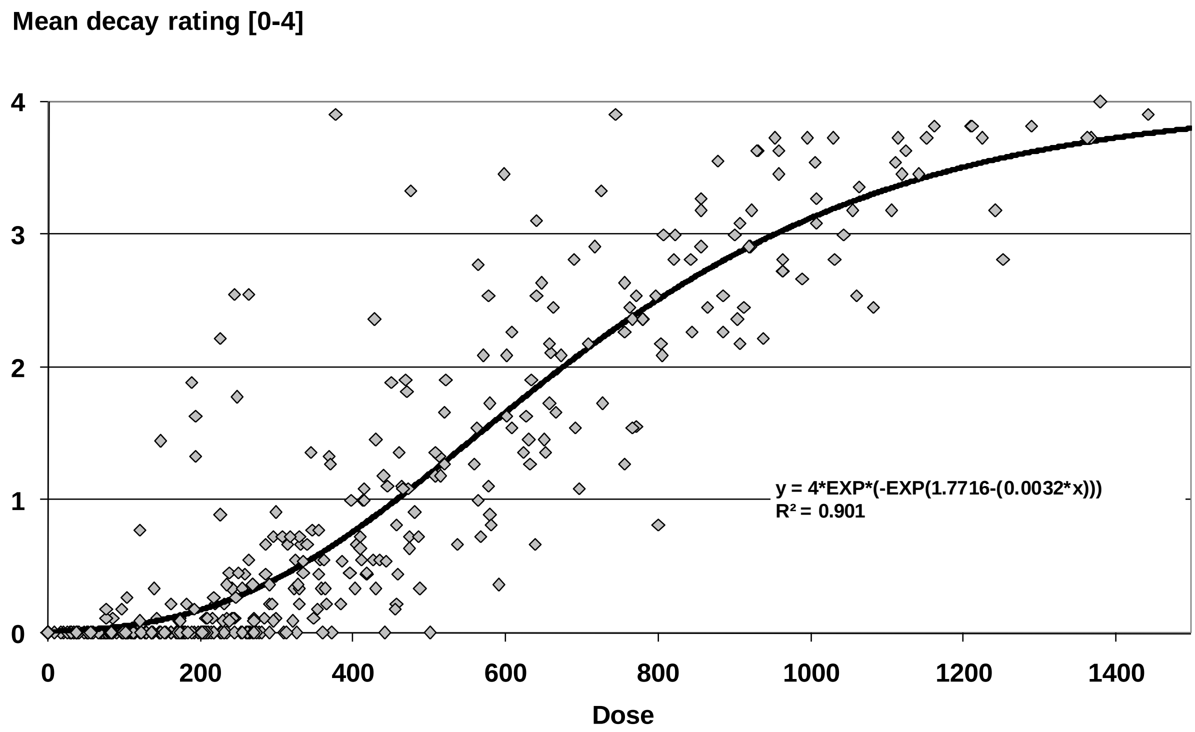

Figure 6: Relationship between the dose and the mean decay rating according to EN 252 (1989) of Scots pine sapwood <u>and</u> Douglas fir heartwood specimens exposed at 28 different field test sites (each dot represents the mean decay rating for one wood species at one exposure site at a certain time of exposure; black line: Gompertz smoothing function).

In general, two different wood species may respond differently in terms of moisture content under the same climate conditions. The MC of Scots pine sapwood in the double layer set up was critically above fibre saturation at nearly all times. In contrast, Douglas fir was much drier and was well below fibre saturation during the summer periods. Consequently, it is insufficient to determine the dose for decay from microclimatic data only, because the substrate wood needs to be considered in terms of its adsorption and desorption properties, which are again determined by its chemical composition and its anatomy (e.g. Rapp et al. 2000; Stirling and Morris 2006). Thus, a direct relationship can only be found between the material climate (long term MC and wood temperature) and decay.

Table 3: Occurrence of different types of decay for Scots pine sapwood and Douglas fir heartwood at the different exposure sites.

Test site and exposure	**Pine sapwood**			**Douglas fir heartwood**		
	Occurrence of					
	Brown rot [%]	**White rot [%]**	**Soft rot [%]**	**Brown rot [%]**	**White rot [%]**	**Soft rot [%]**
Hamburg sun	0	100	9	56	44	0
Hamburg shade	0	82	27	0	67	11
Greenhouse	0	91	64	0	22	11
Greenhouse winter	0	82	64	22	67	33
Reulbach sun	0	46	82	11	0	33
Reulbach shade	0	64	91	11	56	0
Stuttgart sun	0	0	100	0	0	0
Stuttgart shade	9	54	64	67	11	0
Freiburg sun	0	18	100	22	0	22
Freiburg shade	82	9	9	89	0	11
Oberrottweil	0	73	64	0	22	0
Feldberg	0	0	100	0	0	0
Bühlertal	0	91	27	0	78	0
Hornisgrinde	0	100	9	0	11	0
Hinterzarten	0	0	100	0	56	0
Schömberg	9	46	64	0	33	11
Heilbronn/Heidelberg	0	73	82	0	11	33
Dobel	0	64	91	0	33	0
St. Märgen	0	91	36	0	22	0
Uppsala	9	27	82	0	0	44
Ljubljana	100	0	0	33	33	11
Zagreb	27	64	9	0	33	22
London	9	55	64	0	0	0
Garston	27	82	46	56	0	11
Portsmouth	9	82	27	0	11	56
Ghent	9	36	91	0	11	0
Bordeaux	64	64	0	0	0	33
Oslo	0	18	46	0	0	0

4. FUTURE WORK

4.1 Optimization of dose-response functions

Further improvements of the existing dose-response functions are conceivable and will be addressed in future modelling taking into account the results of further field trials:

- A potential time dependence of the dose-response relationship may be caused by the occurrence of different cardinal temperature and MC points for different stages of fungal infestation, e.g. germinating spores and mycelium (Schmidt 2006).
- Initial inhibition of fungal infestation varied between the sites and resulted in differently long time lags. “Activation processes” at the beginning of outdoor exposure should be considered separately (Viitanen et al. 2008).
- Different disturbance variables, e.g. longer periods of dryness or frost, as well as the constancy of the material climate, i.e. the amplitude of moisture and temperature, may affect the progress of decay and could be regarded by weighting intervals of very high or very low decay potential.
- The constancy of the material climate or the amplitude of the material climate parameters respectively may also affect the decay progress.

4.2 Dose-time functions

Dose-response functions permit to estimate the moisture and temperature induced decay potential for any wooden building component and exposure, and thus the service life to be expected. Therefore it is not longer necessary to wait in field trials until decay actually occurs. In fact they rather allow determining dose-time functions for a certain construction detail over a shortened exposure period, e.g. 2-3 years.

The set up of different studies to determine the moisture and temperature induced dose over time for different wood species, commodities, and exposure situations will be presented in part 2 of this series as well as preliminary results.

5. CONCLUSIONS

Considerable differences in decay progress and thus in the expected service life of wood in above-ground exposure were observed between different test sites in Europe and seemed to be strongly influenced by the local climate, but no direct relationship could be established between climatic characteristics in terms of precipitation and temperature and decay. On the other hand, the combined material climatic parameters MC and wood temperature were strongly correlated with decay and feasible dose-response functions were established.

In addition, future work is needed with respect to other wood species, different exposure situations, and especially to the relationship between climate data (precipitation, air temperature) and wood moisture content and may further enhance the applicability of the method. Preliminary results from various current studies aiming on establishing dose-time functions are promising.

6. ACKNOWLEDGEMENTS

We are very grateful for all the support we got from our partners at the "32 sites" during the last nine years! Thanks to Prof. Dr. Joris Van Acker, Dr. Luisa Borges, Dr. Simon Cragg, Dr. Radovan Despot, Dr. David Dickinson, Prof Dr. Rod Eaton, Fred Evans, Marin Hasan, Dr. Miha Humar, Dr. Barbara Illman, Dr. Dennis Jones, Isabelle Le Bayon, Prof. Dr. Thomas Nilsson, Matjaž Pavlič, Prof. Dr. Marko Petrič, Prof. Dr. Franc Pohleven, Dr. Ulrika Råberg, Dr. Michael Ray, Dr. Ed Suttie, Dr. Derek Wallace and to all involved at Menz-Holz, Reulbach, vTI, Hamburg, Leibniz University Hanover, FVA, Freiburg, FMPA, Stuttgart, and at the different DWD meteorological stations.

Furthermore we express our special thanks to the Federal Research Centre for Forestry and Forest Products (BFH), Hamburg, and to the University of Hamburg, Department of Wood Science, where main parts of the experimental work were performed.

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