7.5 Publikation V: Dose-response relationships between wood moisture content, wood temperature, and fungal decay determined for 23 European field test sites

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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 23 different European test sites under different exposure conditions (in total 27 test sets). The material climate in terms of wood moisture content (MC) and wood temperature was automatically monitored over a period of up to seven years and compared with 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 the service life prediction of wood. The "Scheffer Climate Index" based on weather data collected at official meteorological stations at the different test sites was poorly correlated with the corresponding decay progress and was therefore not a suitable tool for estimating site-specific decay potential. In contrast, the use of the combined material climatic parameters MC and wood temperature led a to feasible dose-response function and turned out to be a useful basis for service life prediction of wood.

7.5.1 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 2007). 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. 2007a).

The influence of macro- and microclimates on decay should be especially apparent with "wood moisture content" (MC) and "wood temperature" (Brischke and Rapp 2007). The overall aim of this study was therefore to establish dose-response functions for wood decay with wood MC and temperature. MC, wood temperature, and decay progress were monitored for up to seven years in above ground samples at 27 different exposure sites in Europe.

7.5.2 Material and methods

Field tests

Field test specimens cut from 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 in double layer test rigs (Rapp and Augusta 2004) that consisted of specimens placed horizontally in two layers and exposed above ground producing a decay risk corresponding to European Hazard 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 stakes 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 23 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 temperature were recorded. The characteristic data for the test sites are listed in (Table 7.5-1). Additionally, a second set of specimens at some sites was artificially shaded. “Shade sets” were put in plywood boxes (30x90x90 cm³) covered with fully water-permeable textile sheets, which were transmitting only 10% of the 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 7.5-1). The exposure in shade boxes and the tropical greenhouse was carried out to provoke changes in terms of the microclimate and to promote the conditions for decay.

Table 7.5-1. Characteristic data of the 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	04/2007
Greenhouse	D	35	21.6	4)	6257	3)	07/2000	04/2007
Greenhouse winter	D	35	18.6	4)	4092	3)4)	07/2000	04/2007
Reulbach sun/shade	D	620	7.5	2)	820	1)	07/2000	08/2006
Stuttgart sun/shade	D	459	9.9	2)	741	1)	07/2000	08/2006
Freiburg sun/shade	D	302	12.1	1)	911	1)	07/2000	08/2006
Oberrottweil	D	221	11.7	1)	731	1)	12/2000	08/2006
Feldberg	D	1496	4.3	4)	1588	4)	12/2000	08/2006
Bühlertal	D	465	9.8	5)	1664	5)	12/2000	08/2006
Hornisgrinde	D	1131	6.0	5)	2030	5)	12/2000	08/2006
Hinterzarten	D	887	7.0	5)	1586	5)	12/2000	08/2006
Schömberg	D	635	8.0	4)	954	1)	12/2000	10/2006
Heilbronn/Heidelberg[10)]	D	173/111	11.2/11.7	10)	769/679	10)	12/2000	08/2006
Dobel	D	706	9.0	9)	1473	9)	12/2000	08/2006
St. Märgen	D	908	8.2	1)	1834	1)	12/2000	08/2006
Uppsala	S	7	6.8	5)	579	5)	05/2001	09/2006
Ljubljana	SLO	299	11.3	1)	1330	1)	04/2001	06/2006
Zagreb	HRO	123	10.7	4)	910	4)	08/2002	06/2006
London	GB	62	11.9	8)	649	8)	07/2002	09/2006
Garston	GB	90	10.7	7)	515	7)	07/2002	09/2006
Portsmouth	GB	1	11.6	6)	667	6)	04/2001	09/2006
Ghent	B	9	10.9	1)	758	1)	08/2002	11/2006
Bordeaux	F	4	14.0	5)	798	5)	01/2001	10/2006

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 July 2002-June 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

Decay assessment

The specimens were evaluated yearly by 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). The prevailing type of decay was identified for each species and exposure according to EN 12083-2 (2005).

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. 2007b) and can be summarized in brief as follows: electrodes of polyamide coated stainless steel cables were conductively glued in the specimens. The steel cables were connected to a small data logger (Materialfox Mini, Scanntronik Mugrauer GmbH, Zorneding, Germany), that recorded the electrical resistance of the wood. The data logger were calibrated in a range between 12% and 50% MC (Brischke et al. 2007b). Measurements above fiber saturation were increasingly inaccurate, but still indicated a tendency within the calibration range. Average, 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).

Scheffer Climate Index

An index of the relative site potential to promote decay of off-the-ground wood structures was developed by Scheffer (1971). This Scheffer Climate Index, which is focused on air temperature and distribution of rainfall, is calculated as follows:

$$\text{Scheffer Climate Index} = \frac{\sum_{\text{Jan}}^{\text{Dec}}[(\text{T}-2)(\text{D}-3)]}{16.7}$$

$\sum_{\text{Jan}}^{\text{Dec}}$ sum of the months January to December

T mean day-temperature of the month in °C

D mean number of days with more than 0.25 mm rain per month

In this study the Scheffer Climate Index was calculated monthly, then accumulated for each exposure interval and site. The data were compared with the corresponding decay ratings to assess potential relationships between climate and decay hazard.

7.5.3 Results and discussion

Relationship between time of exposure and decay

The progress of decay revealed high variation between the different exposure sites for both, pine sapwood (Figure 7.5-1) and Douglas fir heartwood (Figure 7.5-2). 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 at the Uppsala site, where decay was least rapid. Thus, obviously two effects lead to the variation in decay progress among the test sites. The time lags between exposure and the first detection of visible decay ranged from 0.4 years in Greenhouse winter to more than 3.8 years in Uppsala (Table 7.5-2). Numerous inhibitory effects on fungal activity, e.g. competition and antagonism between species, inhibitory extractives and insufficient permeability of the wood, potentially cause these time lags (Brischke and Rapp, 2007). 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 maybe also interactions between the incipiently inhibition and the moisture/temperature induced dose.

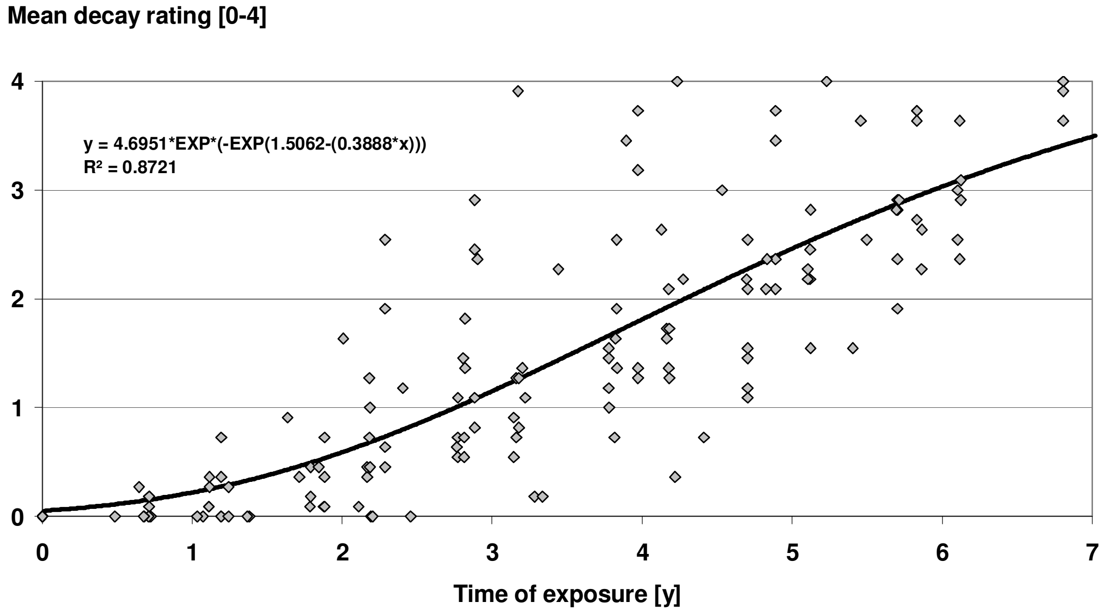

Figure 7.5-1. Relationship between the time of exposure and the mean decay rating according to EN 252 (1989) of Scots pine sapwood specimens exposed at 26 different exposure sites (each dot represents the mean decay rating at one exposure site at a certain time of exposure; black line: Gompertz smoothing function).

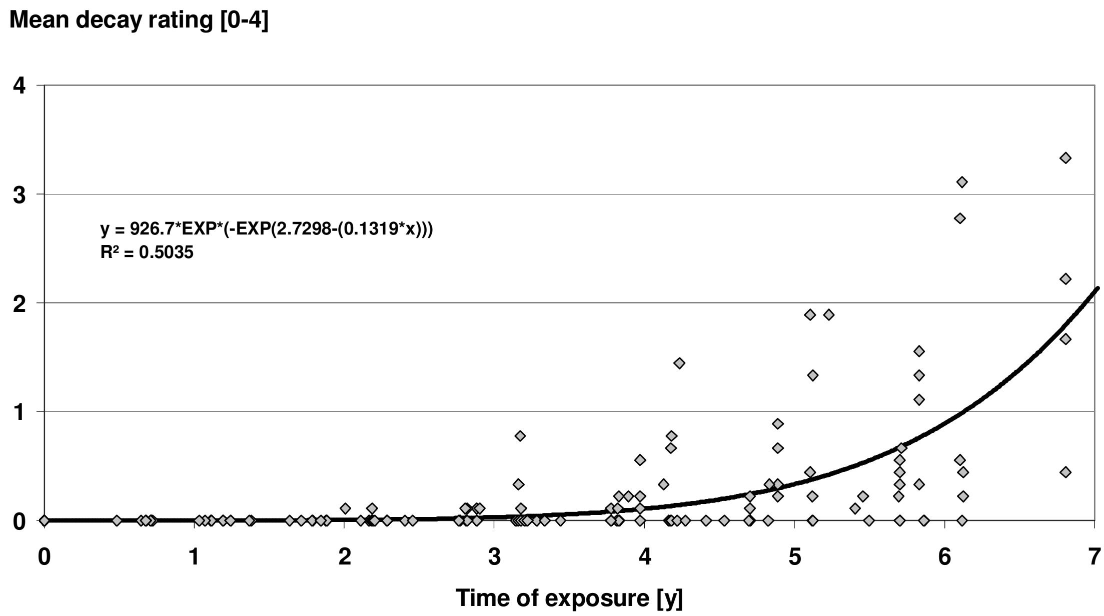

Figure 7.5-2. Relationship between the time of exposure and the mean decay rating according to EN 252 (1989) of Douglas fir heartwood specimens exposed at 26 different exposure sites (each dot represents the mean decay rating at one exposure site at a certain time of exposure; black line: Gompertz smoothing function).

Table 7.5-2. Mean time lag (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	
	Pine sapwood [y]	Douglas fir heartwood [y]
Hamburg sun	2.2	4.3
Hamburg shade	1.7	4.8
Greenhouse	0.9	> 4.7
Greenhouse winter	0.4	> 6.2
Reulbach sun	2.1	> 5.6
Reulbach shade	1.7	> 5.6
Stuttgart sun	1.8	> 6.1
Stuttgart shade	1.2	4.3
Freiburg sun	1.6	> 5.2
Freiburg shade	0.8	> 3.8
Oberrottweil	2.4	> 5.6
Feldberg	1.9	> 5.7
Bühlertal	1.2	> 4.7
Hornisgrinde	1.9	> 5.7
Hinterzarten	1.7	> 5.2
Schömberg	2.2	> 5.9
Heilbronn/Heidelberg	1.5	> 5.0
Dobel	2.5	> 5.9
St. Märgen	1.7	> 5.3
Uppsala	> 3.8	> 5.3
Ljubljana	1.3	> 3.6
Zagreb	1.5	> 3.6
London	> 3.7	> 4.2
Garston	2.1	> 3.9
Portsmouth	0.7	> 5.3
Ghent	2.4	> 4.3
Bordeaux	n.a.	n.a.

n.a. = not available

Relationship between Scheffer Climate Index and decay

The Scheffer Climate Index was calculated monthly for the different test sites and correlated with the corresponding mean decay ratings for pine sapwood exemplarily (Figure 7.5-3). The relationship between the climate index (regarded as dose) and the decay rating (regarded as response) on pine sapwood varied widely among test sites. The inaccuracy of the Scheffer Climate Index was earlier pointed out by De Groot (1982), Norén (2001) and others: additional factors, as mesoclimatic and microclimatic differences among others, are not considered. This coincides with the findings of this study and was especially apparent for the exposure under greenhouse conditions. The Scheffer Climate Index in these exposures was very high due to daily precipitation and constantly high temperatures, whereas the response in terms of decay was comparatively low.

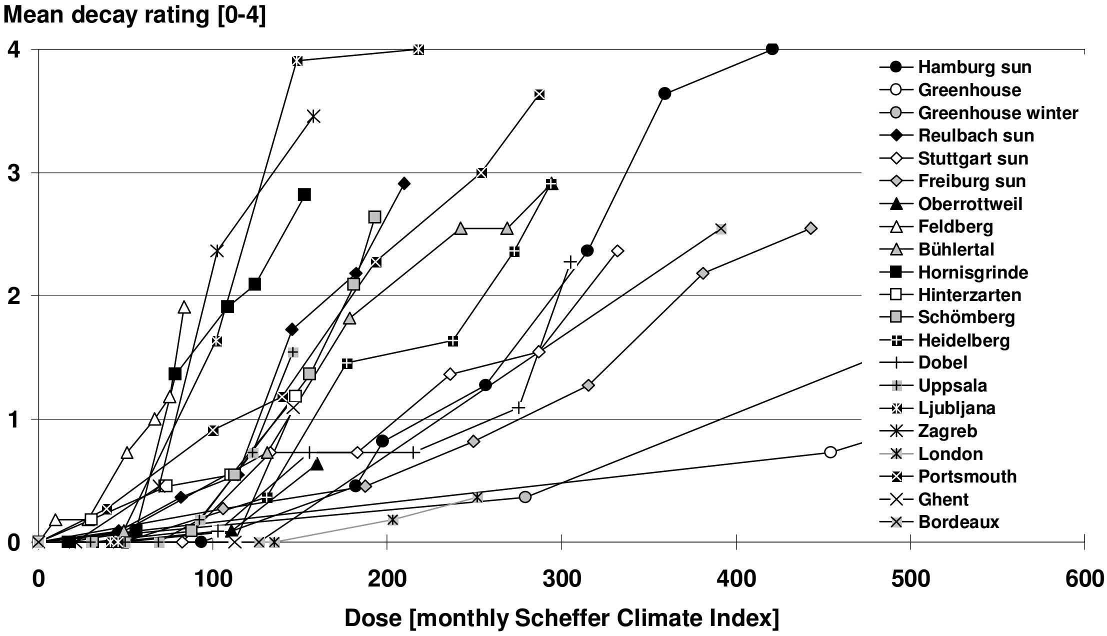

Figure 7.5-3. Relationship between the monthly Scheffer Climate Index and the mean decay rating according to EN 252 (1989) of Scots pine sapwood specimens for different exposure sites.

Even when decay was related to the conditions prevailing during the exposure period, rather than to long-term averages, as recommended by Beesley et al. (1983) and conducted in the present study, no sufficient correlation was obtained. To consider air temperature and rainfall, which both have only an indirect influence on decay, seems to be an oversimplified approach. Therefore the direct decay factors MC and wood temperature were used to establish dose-response functions.

Set up of 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 as follows:

$$d = d_{MC} \cdot d_T$$

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. Figure 7.5-4).

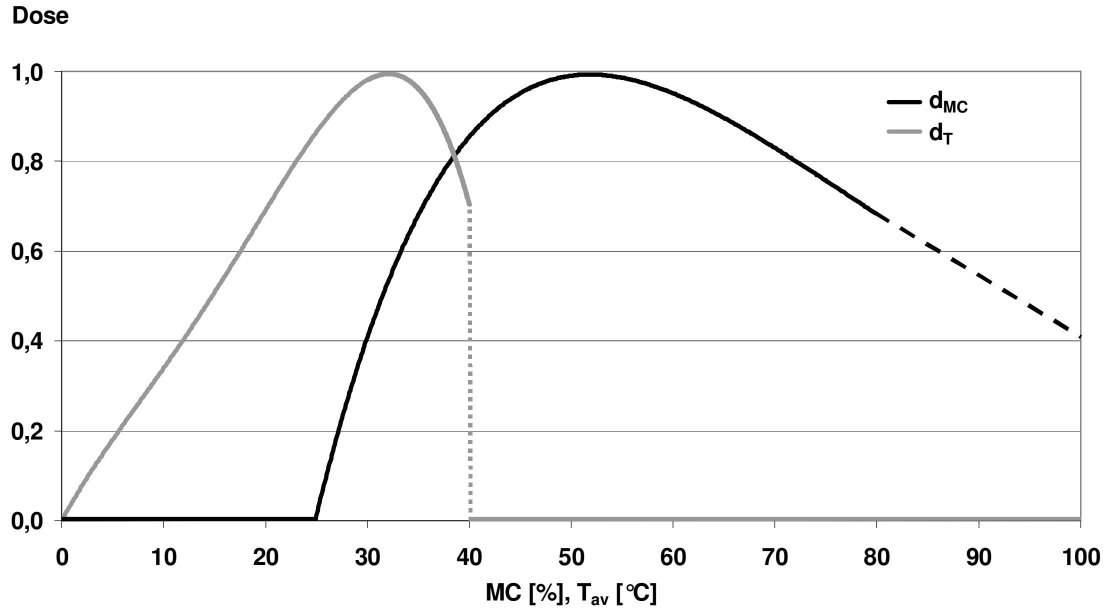

Figure 7.5-4. Relationship between MC and daily moisture induced dose d_{MC}, and between average wood temperature T_{av} and daily temperature induced dose d_T respectively. Dashed black line: MC>80% did not occur, therefore the curve progression is uncertain.

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. The minimum MC for fungal decay needs to be above fiber saturation (Schmidt 2006), otherwise the enzymes released by the fungus that 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 of many relevant basidiomycetes ranges between 35% and 70% (Ammer 1964; Rypáĉek 1966; Viitanen and Ritschkoff 1991; Huckfeldt et al. 2005). The upper moisture limit for most 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 (Ammer 1963; Schuhmacher and Schulz 1992; Schmidt 2006).

In general, the minimum temperature for fungal growth is 0℃, because no liquid water is available in hyphae, provided that the freezing point is not lowered by a modified chemical composition of the hyphae 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℃ (e.g. Wälchli 1977; Schmidt 2006). The optimum for fungal decay however can be different, i.e. lower, from the optimum for fungal growth (Grinda 1975). The maximum for mycelial growth and wood decay by most wood fungi is often 40 to 50℃ (Rypáĉek 1966; Viitanen and Ritschkoff 1991; 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℃ 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, which was computed by NLIN in the SAS® package (cf. Figure 7.5-5). 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℃, with a minimum temperature below –1℃, or with a MC below 25% was set as 0.

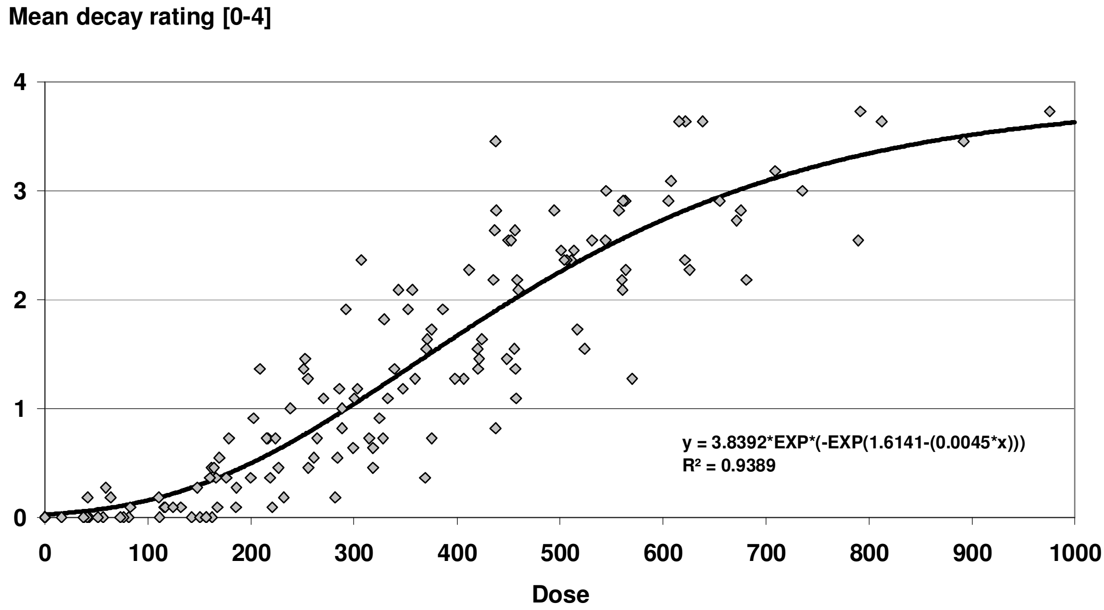

Figure 7.5-5. Relationship between the dose and the mean decay rating according to EN 252 (1989) of Scots pine sapwood specimens exposed at 26 different field test sites (each dot represents the mean decay rating at one exposure site at a certain time of exposure; black line: Gompertz smoothing function).

The computed optimization revealed the following fifth-degree polynomial for the MC induced, and a fourth-degree polynomial for the temperature induced daily dose, as shown in Figure 7.5-4:

$d_{MC} = 6.75•10^{-10}\ MC^5 – 3.50•10^{-7}\ MC^4 + 7.18•10^{-5}\ MC^3 – 7.22•10^{-3}\ MC^2 + 0.34MC – 4.98$

; if MC≥25%

$d_T = 1.8•10^{-6}\ T^4 + 9.57•10^{-5}\ T^3 – 1.55•10^{-3}\ T^2 + 4.17•10^{-2}\ T$

; if T_{min}>-1 °C and T_{max}<40 °C

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

Since brown rot fungi generally have lower moisture minima and optima than white and soft rot fungi (e.g. Viitanen 1997; Schmidt 2006), it seems reasonable to consider them separately to establish dose-response functions. For the time being there are data on brown rot decay from one test site (Ljubljana) only, whereas white rot and soft rot were predominant on pine sapwood at 26 exposure sites and therefore a dose-response function was set up for this combination (Figure 7.5-5). The MC and temperature induced dose correlated well with fungal decay as response (R^2=0.9389).

In general, two different wood species may respond differently in terms of moisture content under the same climate conditions. The MC of 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 accessory ingredients or its anatomical structure (e.g. EN 335-2, 2006; 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.

Future work

Further improvements of the existing dose-response functions are conceivable and should be considered for future modeling:

- The dominating decay type has probably a significant influence on the progress of decay. Therefore the data base needs to be extended, because in this study only one test site revealed brown rot as dominating rot type on pine sapwood. In addition, a sufficient data base in terms of decay ratings for Douglas fir heartwood can be expected within the next two years.
- 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 (Morton and French 1966; Schmidt 2006).
- Different disturbance variables, e.g. longer periods of dryness or frost, may affect the progress of decay and could be regarded by weighting intervals of very high or very low decay potential.

- Exposure in the subtropics and tropics should be addressed, as such climates were so far only considered by means of exposure in a greenhouse.

Coming from applied service life prediction and planning the focus is certainly more on the practicability of the prediction tool, especially on the availability of the data needed. In this regard the use of easily available climate data is desirable, because it is difficult to receive MC and wood temperature data for a particular site. Furthermore, the relation between climate data (precipitation, air temperature) and the material climate strongly depends on the type of exposure (e.g. vertical/horizontal, with/without water traps, covered/non-covered), and therefore more information is needed about the relationship between MC and the amount and duration of rainfall under different exposure situations.

7.5.4 Conclusions

Great 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. However, 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 a feasible dose-response function that was reliable for white and soft rot on pine sapwood was established. Future studies will show, whether the decay type brown rot is also covered with the function or an adjustment of the function is needed.

In addition to the influence of different rot types, 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.

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