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# Studies into Fungal Decay of Wood in Ground Contact—Part 2: Development of a Dose–Response Model to Predict Decay Rate

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**Abstract:** In this article a dose–response model was developed to describe the effect of soil temperature, soil moisture content, and soil water-holding capacity, on the decay of European beech (*Fagus sylvatica*) wood specimens exposed to soil contact. The developed dose–response model represents a step forward in incorporating soil-level variables into the prediction of wood decay over time. This builds upon prior models such as those developed within the TimberLife software package, but also aligns with similar modeling methodology employed for wood exposed above ground. The model was developed from laboratory data generated from terrestrial microcosm trials which used test specimens of standard dimension, incubated in a range of soil conditions and temperatures, for a maximum period of 16 weeks. Wood mass loss was used as a metric for wood decay. The dose aspect of the developed function modelled wood mass loss in two facets; soil temperature against wood mass loss, and soil water-holding capacity and soil moisture content against wood mass loss. In combination, the two functions describe the wood mass loss as a function of a total daily exposure dose, accumulated over the exposure period. The model was deemed conservative, delivering an overprediction of wood decay, or underprediction of wood service-life, when validated on a similar, but independent dataset ($R^2 = 0.65$). Future works will develop similar models for outdoor, field-trial datasets as a basis for service-life prediction of wooden elements used in soil contact.

**Keywords:** in-ground wood decay; soil temperature; soil moisture content; soil water-holding capacity; regression

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## 1. Introduction

When timber is used as the primary structure in a building, it is required to have a service-life as long as the building itself and to withstand the environmental conditions and catastrophes to which it may be exposed. The potential lifespan of a wooden product is described by its durability, and its natural durability may be enhanced by a number of treatments, such as modification, preservation, and coatings. Exposure to moisture in combination with favourable temperature and oxygen supply can leave wood vulnerable to attack by various biotic agents such as fungi, bacteria, and insects [1,2]. Over time, such an attack leads to a loss in functional performance (serviceability) or structural resistance [3,4].

Moisture saturated conditions are particularly prevalent when wood is used in soil contact, leading to a drastically reduced service-life when compared to use in dry, indoor environments [5]. The service-life of a product or component incorporates the concept of durability, but with additional information relating to its usable lifespan. Therefore, quantifying the wood decay process (and therefore durability) is a complex task because of its dependence on, amongst others: wood species; lignin content; element dimension, shape, and configuration of placement; wood treatments and wood-consuming organisms at work; and the antecedent (preceding) conditions [6–9].

To this end, a wood material's durability class and degradation agents associated with a use class are combined to assess the suitability of that wood material (with or without treatment) for the application in mind, with emphasis on maximizing service-life. For example, the European pre-standard, prEN 460:2018 [10], presents such information. Hence, durability and service-life also show a clear link through the overlapping of data requirements used in these study fields [3].

Several researchers have studied and mathematically modelled the service-life of wooden components in the built environment (i.e., aboveground) [4,11–16]. However, research works pertaining to wood degradation in soil contact, ultimately with service-life prediction in mind, are limited by comparison. Notably, the TimberLife software package includes a model for wood used in soil contact [17,18]. The model is extensive, incorporating roughly 80 different wood species, varying intensities of copper- and creosote-based preservative-treated wood, and a variety of maintenance procedures. Climatic data consisting of mean annual precipitation, mean monthly temperature, and the number of dry months in one calendar year, were plotted against the observed depth of decay rates (mm/year) of wooden stakes exposed to soil contact. Equation (1) below shows the modelling principle for untreated wooden stakes exposed to soil contact. The parameter for wood ($k_{wood}$) is based on the natural durability rating of the wood species, with further delineation possible for heartwood, sapwood, and juvenile wood (not shown). The climate parameter ($k_{climate}$) is based on an in-ground decay hazard map that delineates the continent of Australia according to the relative vulnerability of locations to fungal decay due to climatic variation (Figure 1). Numerous researchers have since adapted and calibrated the model to fit particular case studies [19–21].

$$r_{un,stake} = k_{wood} * k_{climate} \tag{1}$$

where:

$r_{un,stake}$ is the depth of decay rate for untreated wooden stakes in soil contact [mm/year];
$k_{wood}$ is the wood parameter based on natural durability rating [scale 1 to 4];
$k_{climate}$ is the climate parameter [scale 0.5 to 3.0, based on scale A to D].

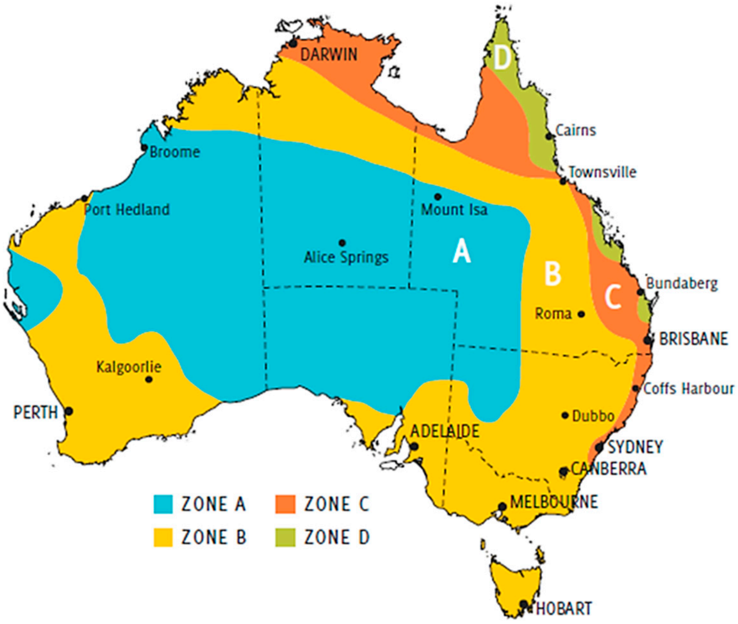

**Figure 1.** In-ground decay hazard map of the continent of Australia delineating relative vulnerability to attack by decay fungi (Zone D has the greatest in-ground decay hazard). Image used with permission from [22].

Studying dose–response relationships, or creating dose-response curves is important in defining allowable exposure levels to particular stimuli. The concept has been applied to wood decay and can be defined as a wooden element's magnitude of response (decay), expressed as a function of a certain exposure time (and intensity) to various decay influencing factors such as temperature and moisture, which provide the means for fungal decay [2].

Over numerous articles, a factorization approach to modelling wood service-life using the dose–response concept was suggested [23–26]. A logistic dose–response model presented in Brischke and Rapp [24], was used to describe the relationship between wood moisture content ($MC_{wood}$), wood temperature, and the resultant wood decay. The model was first developed to describe the development of fungal decay and the corresponding aboveground exposure conditions and follows the physiological requirements (temperature and moisture) of wood-decaying fungi. The total daily dose was assumed to be a function of the moisture- and temperature-induced components (Figure 2). The cumulative total daily dose was calculated as the sum of total daily doses for a certain exposure period ( $n$ days), shown by Equation (2).

$$D(n) = \sum_{1}^{n} D_i = \sum_{1}^{n} (f(D_T(T_i),\ D_{MC}(MC_i))) \quad (2)$$

where:

$D(n)$ is the cumulative total daily dose for a certain exposure period ($n$ days);
$D_i$ is the total daily dose;
$D_T$ is the temperature-induced dose component;
$T_i$ is the average wood temperature for the considered day [°C];
$D_{MC}$ is the moisture-induced dose component;
$MC_i$ is the wood moisture content for the considered day [%].

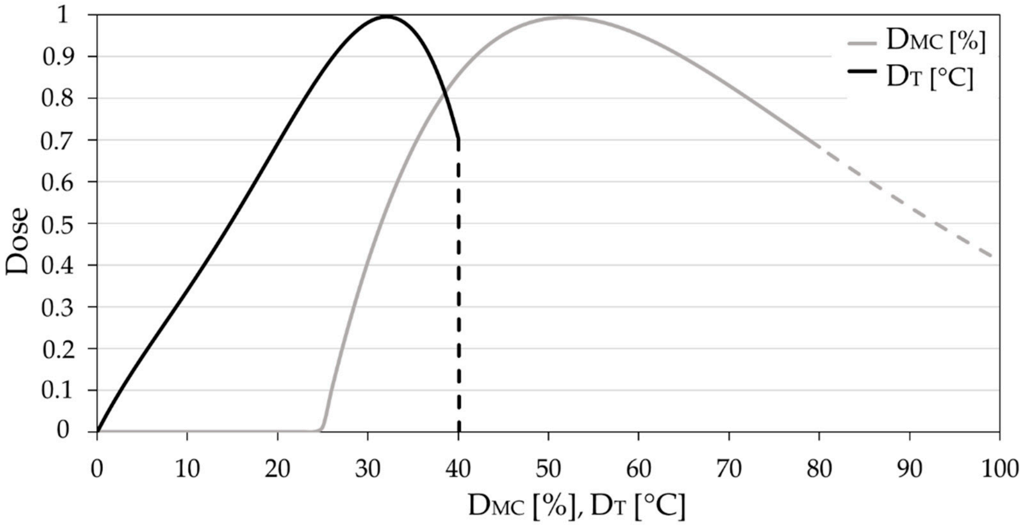

**Figure 2.** Relationship between mean wood moisture content (MC in %) and the daily moisture-induced dose component, and between mean wood temperature ($T$ in °C) and the daily temperature-induced dose component. Dashed lines mean that curve progression is uncertain due to a lack of data beyond zones represented by solid lines. Graph adapted from Brischke et al. [24].

Figure 3 below shows a logistic dose–response model describing wood decay with increments of its sigmoidal-shaped curve aligned to limit states describing the decay progression of a wooden element. As total daily dose days accumulate, so does the depth of decay. Limit state ratings range from 0 to 4, according to the "pick-test" (i.e., decay depth) in the standard EN 252:2015 [27]. The limit state 0 refers to "sound wood," 1 refers to the onset of rot/decay or "slight attack," 2 refers to "moderate attack," 3 refers to "severe attack," and 4 refers to "failure" of the wooden specimen. The blue and green curves in Figure 3 show the relative differences in decay rate between aboveground and in-ground exposure of a wooden element. After installation, wooden elements exposed to soil contact accumulate days of suitable decay conditions (i.e., dose days) far sooner than those exposed aboveground. This means the lag period before the onset of decay is comparably shorter, ultimately resulting in earlier failure of the wooden element. While the green curve is rather a theoretical result, it intends to illustrate this earlier failure that can be expected from a wooden element exposed to soil contact.

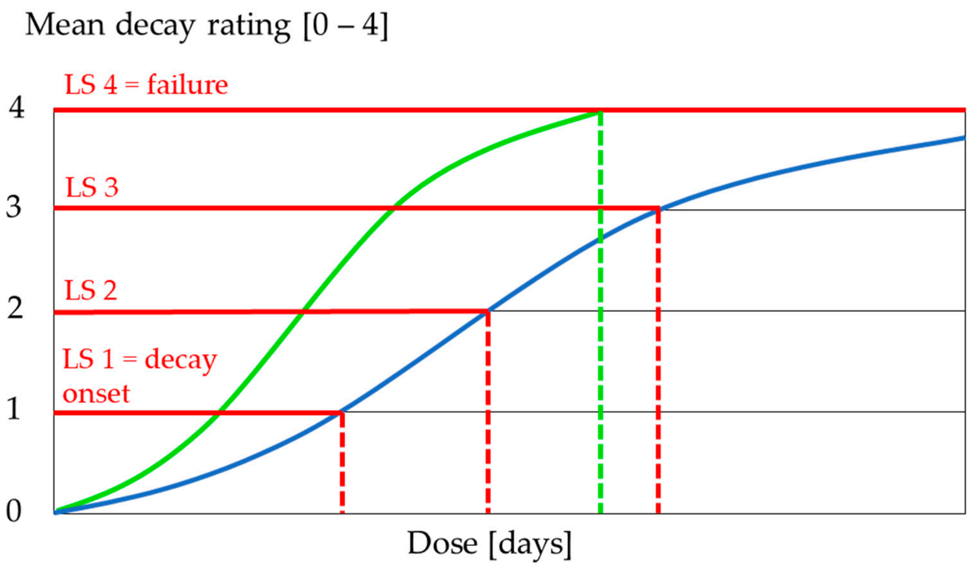

**Figure 3.** Example relationship between cumulative total dose measured in days and mean decay rating according to EN 252:2015 [27] for wood specimens exposed aboveground. LS = limit state; green curve = wooden element exposed in-ground; blue curve = wooden element exposed aboveground. Graph adapted from Brischke and Frühwald Hansson [28].

Although the in-ground and aboveground wood decay modelling approaches presented here are different, similarities between them exist nonetheless. These include the use of climate data in temperature and rainfall and its connection to the physiological requirements of wood-decaying fungi at work. While information regarding the position of decay on the wooden specimen is not always known, there is at least some aspect of spatial decay distribution included in both (i.e., decay depth and rate, and pattern). This is described in part by the respective decay evaluation methods of AWPC:2015 [29] and EN 252:2015 [27]. There is also the possibility to present a decay hazard zone delivering an estimate of service-life, and the natural durability of the wood material (species) is taken into consideration. However, the dose–response approach has not yet been applied to wood exposed to soil contact. The dose–response models developed to date cannot simply be applied to wood decay observed in soil contact. This is due to the differences in measured environmental conditions (i.e., soil remains wetter than air, therefore, in-ground wood remains wetter than aboveground wood), and the differences in wood decay rate since in-ground exposure tends to cause failure far earlier than aboveground exposure situations. Dose curves describing readily measurable variables related to fungal groups tending to be more prevalent in soil contact than aboveground exposure situations (i.e., soil-inhabiting soft-rot fungi) are required to develop dose–response models specific to in-ground exposure (e.g., soil moisture instead of relative humidity). However, any combination of brown-, white-, and/or soft-rot decay would be possible in either exposure situation [30–32], and is, therefore, difficult to predict nonetheless. Brischke and Meyer-Veltrup [33] were indeed able to discern differently sloped logistic curves (such as those in Figure 3) for different predominant decay types observed, namely; brown-rot, and combinations of white- and soft-rot. However, the specimens were still exposed aboveground, meaning the models could not be used to describe in-ground conditions and subsequent wood decay directly.

Aboveground exposure means that the moisture-induced component would likely play a lesser role in wood decay when compared to in-ground exposure.

This article deals with the development of a dose–response model based on a subset of data taken from Marais et al. [34] (i.e., Part 1), to describe wood decay of European beech (*Fagus sylvatica*) in soil contact in the form of wood mass loss ($ML_{wood}$) measured against exposure to temperature and moisture stemming from a range of soil conditions. Recently, Brischke et al. [35] presented a supplementary dataset on the material resistance of wood against biotic agents, based on the relative decay rate prediction method of Meyer-Veltrup et al. [36]. The dataset presents additional wood species with preservative and modification treatments, and their respective water uptake properties, used to predict relative decay rates for both in-ground and aboveground exposure. The factorization-based approach allows for the modification of the material resistance dose relative to an untreated reference. European beech is a common hardwood reference species in many European-based wood durability standards and is more susceptible to soft-rot decay than other softwood reference species such as Scots pine sapwood (*Pinus sylvestris*) [37]. Therefore, it represents a worst-case scenario in the conservativeness of wood decay and subsequent service-life estimates.

The dose–response model was developed from laboratory-based $ML_{wood}$ data in constant temperature conditions, and validated on $ML_{wood}$ data in alternating temperature conditions. Although laboratory-derived wood decay data stems from specimens with smaller dimensions compared to that of field trial specimens, the reason for using the $ML_{wood}$ metric was to start bridging the gap between laboratory and field trial data. Field trial data rather uses the pick-test or decay depth test to assess wood decay. In the future, $ML_{wood}$ can hopefully be used to convert directly to a relevant mechanical property, or loss thereof over time.

The significance of wood durability and service-life research lies in the possibility to plan better. If the use of wood as a building material is to increase in the future, then almost every aspect of its existence and interaction with the environment should be communicable to its users. Ultimately, full supply-chain traceability, accurate service-life prediction, and end-of-life or recycling possibilities, will assist wood in remaining competitive against other building materials.

## 2. Materials and Methods

### 2.1. Mass Loss ($ML_{wood}$) Used in Dose–Response Model Development

European beech (*Fagus sylvatica*) wood specimens of dimension $5 \times 10 \times 100$ mm$^3$ were incubated in terrestrial microcosms (TMCs) for a total of 16 weeks, containing a range of soil substrates with water-holding capacity ($WHC_{soil}$) set to 30%, 60%, and 90%, and soil moisture content ($MC_{soil}$, expressed in $\%WHC_{soil}$) set to 30%, 60%, 70%, 90%, and 95 % $WHC_{soil}$. Additionally, the TMCs were also exposed to a range of constant incubation temperatures, or soil temperature ($T_{soil}$), from 5 to 40 °C, in intervals of 5 °C. Wood specimens were measured for oven-dry mass before and after incubation in TMCs to attain $ML_{wood}$. Subsets of specimens were removed from TMCs and measured for $ML_{wood}$ at different points in the total 16-week incubation period, called specimen removal intervals (measured in days). The soil substrates consisted of horticultural compost produced at the University of Göttingen's North Campus mixed in various quantities with silica sand. The compost comprised of fallen leaves and cuttings from grass and trees. A detailed description of TMC preparation, wooden specimen preparation, and a full listing of results can be found in Part 1 [34].

To understand the composition of data used in this article, Table 1 below shows the $WHC_{soil}$, $MC_{soil}$, and $T_{soil}$ conditions that a subset of European beech wood specimens was exposed to.

**Table 1.** Subset of wood decay data ($ML_{wood}$) with respective moisture and temperature conditions, and specimen removal intervals, taken from Part 1 [34]. The data was used to develop moisture- and temperature-induced dose components towards a dose–response model for wooden specimens exposed to soil contact. Data with blue background was used for the moisture-induced dose component, while data with orange background was used for the temperature-induced component.

| # TMCs | $WHC_{soil}$ [%] | $MC_{soil}$ [%] | $T_{soil}$ (°C) | Intervals | (n) | Total (n) |
|---|---|---|---|---|---|---|
| 1 | 30 | 30 | 20 | 3 | 8 | 24 |
| 1 | 30 | 70 | 20 | 3 | 8 | 24 |
| 1 | 30 | 95 | 20 | 3 | 8 | 24 |
| 1 | 60 | 30 | 20 | 3 | 8 | 24 |
| 6 | 60 | 60 | 5–40 | 6 | 10 | 360 |
| 1 | 60 | 70 | 20 | 3 | 8 | 24 |
| 1 | 60 | 90 | 20 | 3 | 10 | 30 |
| 1 | 60 | 95 | 20 | 3 | 8 | 24 |
| 1 | 90 | 30 | 20 | 3 | 8 | 24 |
| 1 | 90 | 70 | 20 | 3 | 8 | 24 |
| 1 | 90 | 95 | 20 | 3 | 8 | 24 |
| | | | | Total specimens | | 576 |

Wood decay data ($ML_{wood}$) was collected and organised using Microsoft Excel [38]. Further data processing occurred in the R software package [39] and RStudio [40]. RStudio packages "nlme" [41] and "ggplot2" [42] were used for model fitting and data visualization, respectively. Three statistical assumptions of the test data were examined (independence, normality, homoscedasticity). Firstly, even though several wooden test specimens were exposed to soil within the same TMC, it was assumed that each respective specimen's oven-dry mass loss ($ML_{wood}$) was generated independently.

## *2.2. Dose–Response Model Development*

### 2.2.1. Temperature-Induced Dose Component Development

The variable soil temperature ($T_{soil}$) was included in the dose–response model to describe wood temperature conditions. To create this $T_{soil}$ component of the model, data from Part 1 [34], which delivered $ML_{wood}$ across the range of $T_{soil}$ from 5 to 40 °C was used. As seen above in Table 1, the soil conditions linked to this range of $T_{soil}$ were limited to $WHC_{soil}$ of 60% and $MC_{soil}$ at 60 %$WHC_{soil}$. The reason for not including any other soil condition was to isolate the effect of $T_{soil}$ on $ML_{wood}$, while at the same time testing optimal in-ground wood decay conditions, to achieve a worst-case scenario.

Considering the purpose of this article was to deliver a dose–response function, a relationship between $ML_{wood}$ and $T_{soil}$ in terms of dose was required. To define dose for $T_{soil}$ (i.e., stimulus), multiple steps were undertaken to ensure an accurate, but also fair representation of the effect of $T_{soil}$ on $ML_{wood}$ (i.e., response). A mean $ML_{wood}$ value was calculated for each $T_{soil}$ and specimen removal interval (total of 64 entries). These mean $ML_{wood}$ values were then converted to a mean $ML_{wood.rate}$ by dividing the values by their respective specimen removal intervals, Equation (3).

$$ML_{wood.rate} = \frac{ML_{wood}}{specimen\ removal\ interal} \tag{3}$$

where:

$ML_{wood}$ is the oven-dry mass loss of the wooden test specimens [%];
*specimen removal interal* is the period of time the wooden test;
specimens were incubated in soil contact for [days];
$ML_{wood.rate}$ is the oven-dry mass loss per week of the wooden test specimens [$\% \cdot \text{day}^{-1}$].

Then, all mean $ML_{wood.rate}$ values for a given specimen removal interval were assigned a weighted dose value between 0 and 1, with 1 being the highest mean $ML_{wood.rate}$ in the given specimen removal interval. The rest of the mean $ML_{wood.rate}$ values within the same specimen removal interval were assigned a dose relative to the highest mean $ML_{wood.rate}$ value in that specimen removal interval (i.e., dose calculated using the ratio of 1:highest mean $ML_{wood.rate}$). This process was repeated for each of the 8 specimen removal intervals in order to normalize mean $ML_{wood.rate}$ across the $T_{soil}$ range in each specimen removal interval.

After weighted dose values were generated for all 8 specimen removal intervals, dose and their accompanying $T_{soil}$ values were then plotted against one another, and a polynomial regression curve fitted. To improve fit, the 2- and 4-week specimen removal intervals were then excluded due to insufficient mass loss and large variability shown for these incipient decay stages (new total of 6 intervals, therefore 48 entries in total). It was thought that these early decay stages did not reflect sufficient wood decay, which in turn caused outlier values after completing the weighted dose procedure and plotting against their associated $T_{soil}$.

Simple linear regression techniques were applied to fit a polynomial function to $ML_{wood}$ and $T_{soil}$ with an Ordinary Least Squares (OLS) optimization procedure, thereby defining a relationship between the two variables in terms of dose. Assumptions relating to independence, normal distribution, and homogeneity of variance (homoscedasticity) should be adhered to for OLS model fitting to hold true. Therefore, the Shapiro-Wilk test was used to test for a normal distribution of the residuals of the fitted model. This delivered a *p*-value, which was compared with a significance level ($\alpha$ of 0.05), which meant that the null hypothesis of normal distribution of the residuals was accepted if the *p*-value was greater than 0.05. Additionally, a visual inspection was carried out whereby a quantile-quantile (Q–Q) plot of the residuals was drawn to assess whether the cluster of points formed a straight line [43]. To test for homoscedasticity of the residuals, a visual inspection was also carried out whereby the residuals were plotted against the fitted values to verify that the cluster of points did not show any particular trend [43].

### 2.2.2. Moisture-Induced Dose Component Development

The variables soil water-holding capacity ($WHC_{soil}$) and soil moisture content ($MC_{soil}$) were included to describe soil moisture conditions, which in turn described wood moisture conditions ($MC_{wood}$). To create this moisture-induced component of the dose–response model, data from Part 1 [34], which delivered $ML_{wood}$ across a range of $WHC_{soil}$ set to 30%, 60%, and 90% and $MC_{soil}$ set to 30%, 60%, 70%, 90%, and 95 % $WHC_{soil}$ were used. As seen above in Table 1, the $T_{soil}$ conditions linked to this range of $ML_{wood}$ input data was limited to $T_{soil}$ of 20 °C. The reason for limiting $T_{soil}$ to 20 °C was to once again isolate the effect of $WHC_{soil}$ and $MC_{soil}$ on $ML_{wood}$. A mean $ML_{wood}$ was calculated for each $WHC_{soil}$, $MC_{soil}$, and specimen removal interval combination (total of 30 entries). These mean $ML_{wood}$ values were then converted to a mean $ML_{wood.rate}$ rate by dividing the values by their respective specimen removal intervals [days] as in Equation (3).

Again, as with the $T_{soil}$ dose component, all mean $ML_{wood.rate}$ values within a given specimen removal interval (3 different intervals, see Table 1) were assigned a weighted dose value between 0 and 1, with 1 being the highest mean $ML_{wood.rate}$. The rest of the mean $ML_{wood.rate}$ values within the same specimen removal interval then had a weighted dose assigned (i.e., calculated) relative to the highest mean $ML_{wood.rate}$ value for that specimen removal interval.

After weighted dose values were generated for the three removal intervals of all specimens, multiple linear regression was applied to use both $WHC_{soil}$ and $MC_{soil}$ together as input variables for prediction of dose with optimization for the best fitting of the model using OLS. The reason for choosing OLS initially was for the purpose of obtaining an $R^2$ value which is a commonly accepted measure for goodness-of-fit. Subsequent investigation into the adherence of the assumptions of normality and homoscedasticity yielded significant results, meaning the assumptions were not met (especially homoscedasticity). To solve the problem of heteroscedasticity, fixed effects maximum likelihood optimization procedures from the ''nmle'' package [41] in RStudio [40], which included a variance model, were applied to deliver a linear polynomial model capable of predicting dose as output using $WHC_{soil}$ and $MC_{soil}$ as input.

### 2.2.3. Cumulative Total Daily Dose Model Development

As with earlier dose–response models related to wood decay [24], the total daily dose was assumed to be a function of the moisture-induced and temperature-induced components with cumulative total daily dose calculated as the sum of total daily doses for a certain exposure period.

The combination of the two dose components $T_{soil}$, and $WHC_{soil}$ and $MC_{soil}$, translates to the temperature and moisture requirements of wood-decaying fungi present when wood is utilized in soil contact. However, in order to classify the effect of the two environmental parameters over an exposure period per specimen, a total daily (dose) effect was quantified by simply multiplying the output of each of the two component models with one another. This total daily dose was then multiplied over the exposure period (measured in days and therefore weeks) to deliver a cumulative total daily dose for the exposure period and conditions, per specimen.

This created a scatter plot of $ML_{wood}$ vs. cumulative total daily dose, to which once again a simple linear regression was applied with OLS optimization. Investigation into adherence of the assumptions for normality and homoscedasticity was not successful, resulting in the exploration of maximum likelihood optimization techniques, where homoscedasticity was not required. Finally, a linear regression model with maximum likelihood optimization was produced.

Table 2 below shows the total number of specimens, taken from Part 1 [34], in which the respective temperature and moisture dose components were calculated in order to develop a model for cumulative total daily dose.

**Table 2.** A subset of wood decay data ($ML_{wood}$) with respective moisture and temperature conditions, taken from Part 1 [34], with moisture- and temperature-induced dose components calculated to deliver a model describing $ML_{wood}$ as a function of cumulative total daily dose.

| # TMCs | $WHC_{soil}$ [%] | $MC_{soil}$ [%] | $T_{soil}$ (°C) | Intervals | (n) | Total (n) |
|---|---|---|---|---|---|---|
| 1 | 30 | 30 | 20 | 3 | 8 | 24 |
| 1 | 30 | 70 | 20 | 3 | 8 | 24 |
| 1 | 30 | 95 | 20 | 3 | 8 | 24 |
| 1 | 60 | 30 | 20 | 3 | 8 | 24 |
| 8 | 60 | 60 | 5–40 | 8 | 10 | 640 |
| 1 | 60 | 70 | 20 | 3 | 8 | 24 |
| 1 | 60 | 90 | 5–40 | 8 | 10 | 640 |
| 1 | 60 | 95 | 20 | 3 | 8 | 24 |
| 1 | 90 | 30 | 20 | 3 | 8 | 24 |
| 1 | 90 | 70 | 20 | 3 | 8 | 24 |
| 1 | 90 | 95 | 20 | 3 | 8 | 24 |
| | | | | Total specimens | | 1496 |

## *2.3. Model Validation Procedure*

Once a model for cumulative total daily dose was developed, a procedure for testing the universal application of the model was initiated. Thus, the validity of the developed dose–response model was tested. To adequately test the model's predictive strength meant once again selecting a subset of data from Part 1 [34], which was not used to create the model, but at least reflected similarities in data origin while capturing variability in exposure conditions. Therefore, it made sense to select a subset of $ML_{wood}$ data limited to alternating $T_{soil}$. This subset was similar in test setup and soil moisture conditions ( i.e., $WHC_{soil}$ and $MC_{soil}$), but also variable enough in $T_{soil}$ conditions to capture a range of exposure possibilities, more reflective of real-world conditions where daily and seasonal temperature fluctuations are expected. The alternating $T_{soil}$ data was also not considered in the model's developmental phase and would, therefore, pose as an applicable case study dataset. Table 3 below shows this subset of data, complete with alternating $T_{soil}$ cycles, where $T_{soil}$ was alternated (changed) to the stipulated values once every 7 days.

**Table 3.** Subset of wood decay data ($ML_{wood}$) with respective moisture and temperature (alternating) conditions, taken from Part 1 [34], used to test the goodness-of-fit of the developed dose–response model for wooden specimens exposed in soil contact.

| # TMCs | $WHC_{soil}$ [%] | $MC_{soil}$ [%] | $T_{soil}$ (°C) | Intervals | (n) | Total (n) |
|---|---|---|---|---|---|---|
| 1 | 60 | 60 | 10/20 | 8 | 10 | 80 |
| 1 | 60 | 60 | 10/30 | 8 | 10 | 80 |
| 1 | 60 | 60 | 20/30 | 8 | 10 | 80 |
| 1 | 60 | 90 | 10/20 | 8 | 10 | 80 |
| 1 | 60 | 90 | 10/30 | 8 | 10 | 80 |
| 1 | 60 | 90 | 20/30 | 8 | 10 | 80 |
| | | | Total specimens | | | 480 |

Actual versus predicted values of $ML_{wood}$ (per specimen) were used to test the goodness-of-fit of the developed dose–response model. This entailed applying the respective moisture- and temperature-induced dose component calculations to the exposure conditions for the 16-week exposure period. The cumulative total daily dose was then calculated per specimen (for its respective exposure period), with predicted $ML_{wood}$ and actual $ML_{wood}$ plotted on a scatter plot against one another. Ideally, a 1:1 relationship between predicted and actual $ML_{wood}$ values would mean a perfect fit of the dose–response model to the observed wood decay. This meant fitting a straight line with a gradient of 0.5 (origin at 0) through the scatter plot of actual versus predicted values and assessing the residuals of the predicted values to the plotted straight line. A goodness-of-fit ($R^2$) value [44] was then calculated for the model; Equations (4)–(6).

$$R^2 = \frac{1 - s^2}{Var(Y')} \tag{4}$$

$$s^2 = \frac{SSE}{(n' - p)} \tag{5}$$

$$SSE = \sum_{i=1}^{n'} \left(Y_i' - \hat{Y}_i'\right)^2 \tag{6}$$

where:

$R^2$ is the goodness-of-fit of the developed model;
$s^2$ is the residual variance of the sum of squares of the residuals;
$n'$ is the number of $ML_{wood}$ measurements;
$p$ is the number of freely estimated parameters in the model;
$Y_i'$ are the actual $ML_{wood}$ values;
$\hat{Y}_i'$ are the predicted $ML_{wood}$ values;
$SSE$ is the sum of squares of the residuals;
$Var(Y')$ is the empirical variance of the actual $ML_{wood}$ values.

## 3. Results and Discussion

### *3.1. In-Ground Dose–Response Model*

### 3.1.1. Soil Temperature ($T_{soil}$) Dose Model

Equation (7) below presents a model for the temperature-induced dose component with Figure 4 below showing a graphical representation of the component model where simple linear regression techniques were applied to fit a polynomial function using the OLS optimization procedure. The polynomial function was created from 48 different weighted dose entries, corresponding to $ML_{wood}$ for eight different incubation temperatures ($T_{soil}$) at six specimen removal intervals. These six weighted dose points for each $T_{soil}$ can be seen on the graph. Important to note is that for each of the six specimen removal intervals, optimum wood decay occurred at $T_{soil}$ of 35 °C, meaning the highest mean $ML_{wood.rate}$. Therefore, all specimens incubated in TMCs with $T_{soil}$ of 35 °C, for all six specimen removal intervals received a weighted dose value of 1.0. Optimum $T_{soil}$ of 35 °C also represents the major turning point of the polynomial function where the wood decay rate tends to slow down. The temperature-induced dose component becomes zero when $T_{soil}$ exceeds 40 °C or drops below 0 °C. This reasoning was based on the data gathered in this study (i.e., $T_{soil}$ from 0 to 40 °C), which represents the model's range, but also on the physiological requirements of wood-decaying fungi, whereby wood decay slows down drastically or ceases entirely at temperatures below 0 °C, and above 40 °C [45]. However, studies of wooden expedition huts in Antarctica were able to find evidence of soft-rot, meaning that even consistent sub-zero temperatures cannot impede wood decay indefinitely [46].

$$\begin{gathered} D_T(T_{soil}) = 0;\ \text{if } T_{soil,min} < 0\ ^\circ\text{C or if } T_{soil,max} > 40\ ^\circ\text{C} \\ D_T(T_{soil}) = b_1 * T_{soil} + b_2 * T_{soil}^2 + b_3 * T_{soil}^3 + b_4 * T_{soil}^4 + b_5 * T_{soil}^5\ ;\ \text{if } T_{min} \geq 0\ ^\circ\text{C or if } T_{max} \leq 40\ ^\circ\text{C} \end{gathered} \tag{7}$$

where:

$D_T$ is the temperature-induced dose component;
$T_{soil}$ is the mean soil temperature for the considered day [°C];
$T_{soil,min}$ is the minimum allowable soil temperature for the considered day [°C];
$T_{soil,max}$ is the maximum allowable soil temperature for the considered day [°C].
$b_1 = 0.03267$
$b_2 = 0.003112$
$b_3 = -0.0003564$
$b_4 = 0.00001262$
$b_5 = -0.0000001457$

In addition to a Shapiro-Wilk test delivering a non-significant $p$-value (i.e., $p > 0.05$), a visual inspection of the residuals of the fitted polynomial function was carried out using a Q–Q plot (Appendix A: Figure A1). The point clustering followed a straight line, therefore, verifying a normal distribution of the residuals. Homoscedasticity of the residuals was then assessed using a residuals vs. fitted values plot (Appendix A: Figure A2), with no particular trend shown (i.e., straight line). The temperature-induced dose component model adhered to all three assumptions of normality, homoscedasticity, and independence.

Another aspect regarding the temperature-induced component is the soil's ability to conduct temperature or heat energy. In outdoor conditions, a wooden element in soil contact is exposed to different temperatures above and below the soil surface, which means a gradient of decay risk can exist. Marais et al. [47] point out an array of decay risk factors along the vertical section of an in-ground wooden element. For example, a position on the wooden element corresponding to the air–soil transition zone is likely to experience the highest decay risk, becoming the ultimate point of failure of the element. This is where soil surface moisture infiltrates easily, favourable oxygen levels and temperatures exist, and where fungal attack can occur from both established fungal mycelium in the soil and spores from the air. In the TMC setup used in this study, ambient air temperature and $T_{soil}$ were kept constant through the use of conditioning/incubation chambers. However, important for future models that describe actual outdoor exposure conditions, will be the position of the temperature measurement. The thermodynamic properties of soil could be considered additionally, whereby $MC_{soil}$ can influence the accumulation, dissipation, and transfer of heat energy in soils [48]. This naturally brings about differences in soil and ambient air temperatures on an hourly, daily, and seasonal timescale. To this end, the temperature-induced component model presented in this article strives for soil temperature corresponding to $T_{soil}$ just below the soil surface measured at constant soil moisture conditions of $WHC_{soil}$ at 60% and $MC_{soil}$ at 60% $WHC_{soil}$.

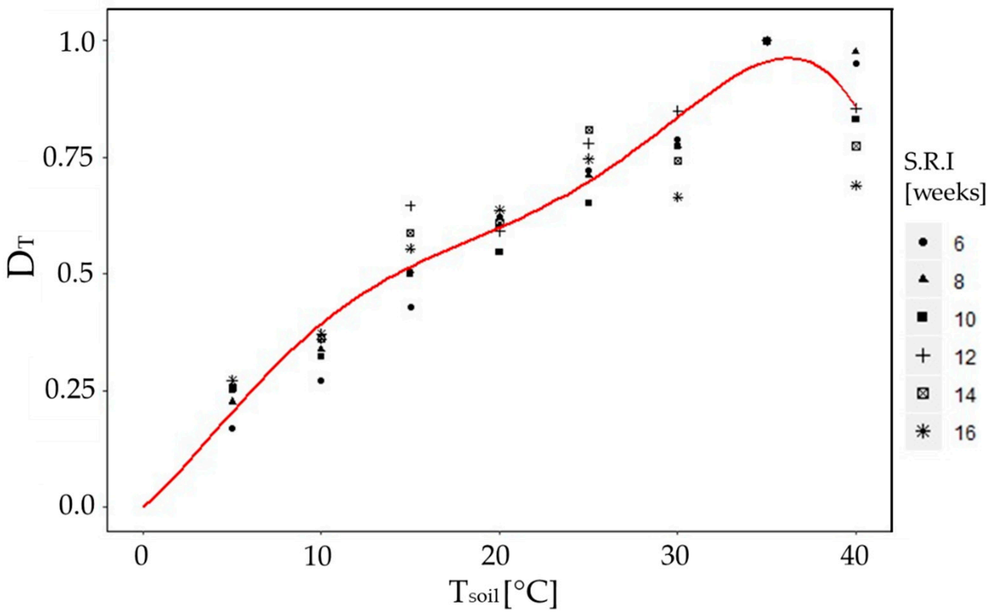

**Figure 4.** Soil temperature ($T_{soil}$) plotted against dose to show the temperature-induced dose component model for European beech wood exposed to soil contact. The red line is a polynomial function fitted using the OLS optimization procedure. $R^2 = 0.9888$. S.R.I. = specimen removal interval measured in weeks.

### 3.1.2. Soil Water-Holding Capacity ($WHC_{soil}$) and Moisture Content ($MC_{soil}$) Dose Model

Equation (8) below presents a linear polynomial model for the moisture-induced dose component. The model was developed using the maximum likelihood optimization procedure and is capable of predicting dose as output using $WHC_{soil}$ and $MC_{soil}$ as input. As with the temperature-induced dose component model, the moisture-induced dose component becomes zero when the soil substrate is unable to facilitate fungal decay. This consists of a combination of the soil's inoculum potential and a suitable moisture source. Additionally, a functional range of input measurements for $WHC_{soil}$ and $MC_{soil}$ are given, but this differs from the temperature-induced model where the range was limited to the range of $T_{soil}$ tested. The functional range of the $MC_{soil}$ input values was limited by the dose output values, whereby input values from 90 to 95% $WHC_{soil}$ delivered negative dose values. This had to be accounted for by limiting the maximum input value for $MC_{soil}$ to 90% $WHC_{soil}$. Input values for $WHC_{soil}$ were limited to the tested range (30 to 90%).

Irrespective of the soil's inoculum potential, without a sufficient moisture source in the soil substrate, $MC_{wood}$ is also too low to facilitate fungal decay. The minimum $MC_{wood}$ for fungal growth is in the region of 20 to 30% [49]. The optimum for many relevant basidiomycetes (brown- and white-rot) ranges between $MC_{wood}$ of 35 and 70% [50], while soft-rotting fungi (Ascomycetes and Deuteromycetes) can cope with comparably higher $MC_{wood}$. Furthermore, prominent unsterile soil-bed test standards, such as CEN 15083-2:2005 [51] require $MC_{soil}$ to be fixed at 95 %$WHC_{soil}$, in order to specifically isolate soft-rotting wood decay activity. Brown-, white-, and soft-rot fungi, can all be found on wood utilized in soil contact.

$$D_u(u_{soil}) = 0\ ;\ \text{if } 30\% > WHC_{soil} > 90\%;\ \text{or if } 30\% WHC_{soil} > MC_{soil} > 90\% WHC_{soil}$$
$$D_u(u_{soil}) = b_1 * WHC_{soil} + b_2 * MC_{soil} + b_3 * MC_{soil}^2 + b_4 * MC_{soil}^3\ ; \tag{8}$$
$$\text{if } 30\% < WHC_{soil} < 90\%;\ \text{or if } 30\% WHC_{soil} < MC_{soil} < 90\% WHC_{soil}$$

where:

$D_u$ is the moisture-induced dose component;
$u_{soil}$ is the moisture-induced component comprising of a combination of soil water-holding capacity ($WHC_{soil}$) and soil moisture content ($MC_{soil}$) for the considered day [%];
$WHC_{soil}$ is the soil water-holding capacity [%];
$MC_{soil}$ is the soil moisture content [% $\text{WHC}_{\text{soil}}$];
$b_1 = 0.008449060$
$b_2 = -0.015157741$
$b_3 = 0.000519323$
$b_4 = -0.000004230$

### 3.1.3. Cumulative Total Daily Dose Model

Equations (9)–(11) present the model for cumulative total daily dose where the sum of total daily doses consisting of moisture- and temperature-induced components, for a given exposure period, can deliver an expected wood decay ($\text{ML}_{\text{wood}}$) value. The input data and linear regression function developed for cumulative total daily dose are represented graphically in Figure 5. It also shows the clear problem of heteroscedasticity of the residuals, that with increasing dose days, $\text{ML}_{\text{wood}}$ shows an increased range between minimum and maximum values. Maximum likelihood optimization techniques (which included a variance model) were subsequently used to deliver the linear model of Equation (11).

$$D = D_T[T_{soil}] * D_u[u_{soil}]\ ;\ \text{if both } D_u > 0 \text{ and } D_T > 0 D = 0\ ;\ \text{if } D_u = 0 \text{ or } D_T = 0 \tag{9}$$

$$D(n) = \sum_1^n D_i = \sum_1^n (f(D_T(T_i),\ D_u(u_i))) \tag{10}$$

$$ML_{wood} = 0.6914485 * D(n) \tag{11}$$

where:

$D(n)$ is the cumulative total daily dose for the considered exposure period [];
$D$ is the total daily dose;
$D_T$ is the temperature-induced dose component;
$D_u$ is the moisture-induced dose component;
$T_{soil}$ is the mean soil temperature for the considered day [°C];
$u_{soil}$ is the moisture-induced component comprising of a combination of soil water-holding capacity ($WHC_{soil}$) and soil moisture content ($MC_{soil}$) for the considered day [%];
$ML_{wood}$ is the oven-dry mass loss of the wooden test specimens [%].

The TimberLife software package takes both $\text{WHC}_{\text{soil}}$ and $\text{MC}_{\text{soil}}$ into consideration, however not in the same manner as the moisture-induced model presented in this article. Wang et al. [18] used computations of soil matric potential ($\Psi_{\text{m}}$) to show the significance of the number of dry months in one calendar year. This approach was therefore rather binary, where the soil was either wet and allowed decay to occur, or dry from insufficient rainfall (<5 mm), to where the outer surface of the in-ground wooden element dried below fibre saturation and inhibited decay. In short, soil matric potential can describe the soil particle size distribution and the interaction between the solid soil fraction, soil pores (air), and the soil moisture fraction. Although theoretical, a soil condition of permanent wilting point ($\Psi_{\text{m}}$ = −1.5 Mpa), correlated to these intermittent rainfall months and observed wood decay patterns. This brought some definition to soil moisture in the context of TimberLife's in-ground wood decay model, but these rainfall measurements only indirectly described a range of soil particle size distributions and soil moisture conditions.

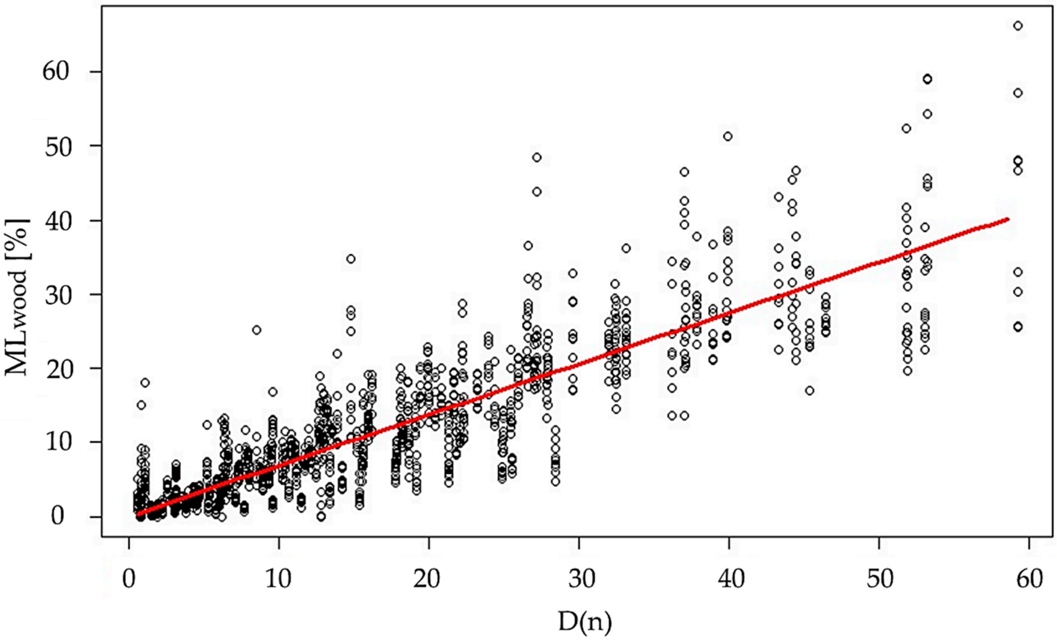

**Figure 5.** Relationship between dose and wood decay ($ML_{wood}$) of European beech wood specimens exposed to soil contact. Each point represents the measured $ML_{wood}$ of a wooden specimen incubated under certain temperature and moisture conditions after a certain exposure period. The red line is a linear function developed using maximum likelihood optimization techniques.

### *3.2. In-Ground Dose–Response Model Validation*

Figure 6 below shows the results from the model validation procedure whereby the predictive accuracy of the cumulative total daily dose model of Equation (11) was assessed. A subset of data describing $ML_{wood}$ for alternating temperature-induced conditions taken from Part 1 [34] was used. The data was independent of that used to construct the model of Equation (11), but described soil conditions with similar moisture conditions. The data points in Figure 6 represent actual $ML_{wood}$ values on the Y-axis and their predicted $ML_{wood}$ values on the X-axis. The red line represents an ideal, 1:1 relationship of the model's prediction accuracy, meaning that the model is currently overpredicting $ML_{wood}$ since most of the points are situated beneath the red line. Underprediction of $ML_{wood}$ would see most of the points situated above the red line, while ideal prediction accuracy would see all the points situated closely to the red line (slightly above and/or below), across the whole prediction range. Residuals from the red line to the predicted values were used to calculate a "goodness-of-fit" criteria ($R^2$ = 0.66).

The in-ground dose–response model presented in this article sees an equal proportionality of the temperature- and moisture-induced components to one another in calculating total daily dose; Equation (9). This differs from previously developed aboveground dose–response models where the calculation of total daily dose is rather more complex. Factors are applied to each component, changing the proportionality of the temperature- and moisture-induced components to one another. A similar procedure was followed for the development of the total daily dose in this article but was ultimately decided against, since no combination of arbitrarily applied disproportionality improved the goodness-of-fit of the model when applied to the validation dataset. For now, the in-ground model sees an equal contribution of both components to the total daily dose.

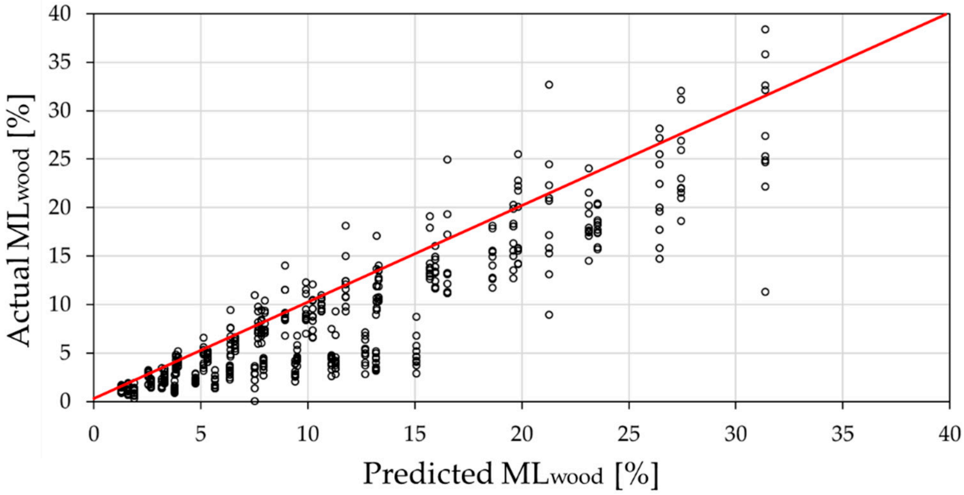

**Figure 6.** Relationship between actual and predicted values of an independent subset of $ML_{wood}$ data describing alternating temperature-induced conditions. The red line shows an ideal, 1:1 prediction accuracy of the cumulative total daily dose model to which the predicted values were compared. $R^2 = 0.65$.

## 4. Conclusions

This article presents a dose–response model for in-ground wood decay of European beech wood (*Fagus sylvatica*). The data used to construct the model described wood decay ($ML_{wood}$) in laboratory-based terrestrial microcosm tests. Two isolated components of soil temperature and soil moisture define the conditions (dose) that deliver wood decay (response). The model was developed from $ML_{wood}$ data for constant temperature conditions and validated on $ML_{wood}$ data for alternating temperature conditions. Important points to note concerning the model and modelling process:

- Soil temperature ($T_{soil}$) describes conditions related to the temperature-induced dose component. Constant $T_{soil}$ was tested in this study;
- Both soil water-holding capacity ($WHC_{soil}$) and soil moisture content ($MC_{soil}$) describe conditions related to the moisture-induced component;
- The temperature- and moisture-induced dose components are multiplied with each other in a 1:1 ratio to deliver a total daily dose;
- The sum of cumulated total daily doses over an exposure period delivers the total number of dose days and a corresponding wood decay ($ML_{wood}$) value [%]. Cumulative total dose days should however not be confused with total exposure days;
- Total daily dose is considered zero when temperature- and/or moisture-induced conditions lie outside of the ranges tested and presented in this study. The temperature and moisture ranges tested in this study were also inspired by the physiological requirements of wood-decaying fungi, in general;
- In future models, these physiological requirement ranges can be expanded to include fungal groups more prevalent in soils;
- When validated on an independent dataset that tested alternating $T_{soil}$, the model overpredicted wood decay. If interpreted directly, this would mean a conservative prediction (or underprediction) of wood service-life;
- Future work will look at incorporating additional components to the dose concept such as soil pH and organic matter content.
- Additionally, the model will be expanded to incorporate wood decay from field trials making use of larger specimens and more wood species, where $ML_{wood}$ can be linked to decay rating and mechanical property loss, ultimately leading to realistic predictions of wood service-life.

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## Appendix A

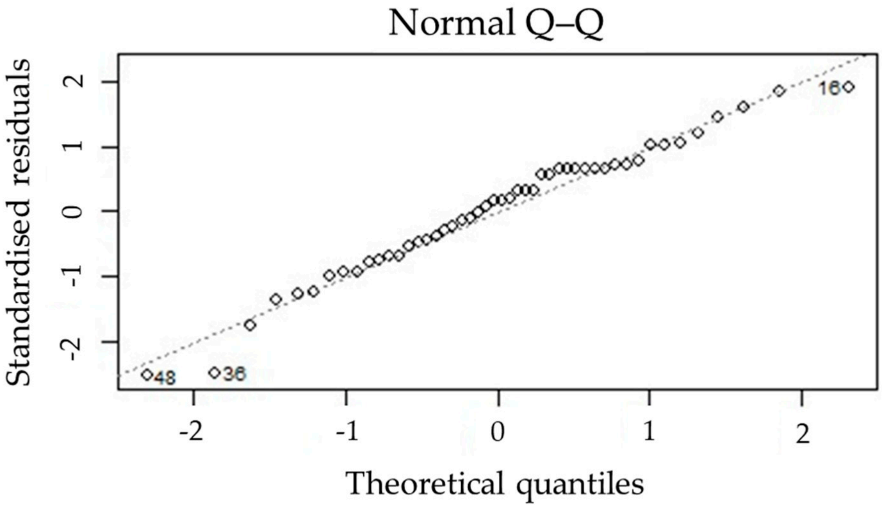

**Figure A1.** Quantile–quantile (Q–Q) plot of the residuals for the temperature-induced dose component model. The straight-line clustering suggests a normal distribution of the residuals of the fitted polynomial function.

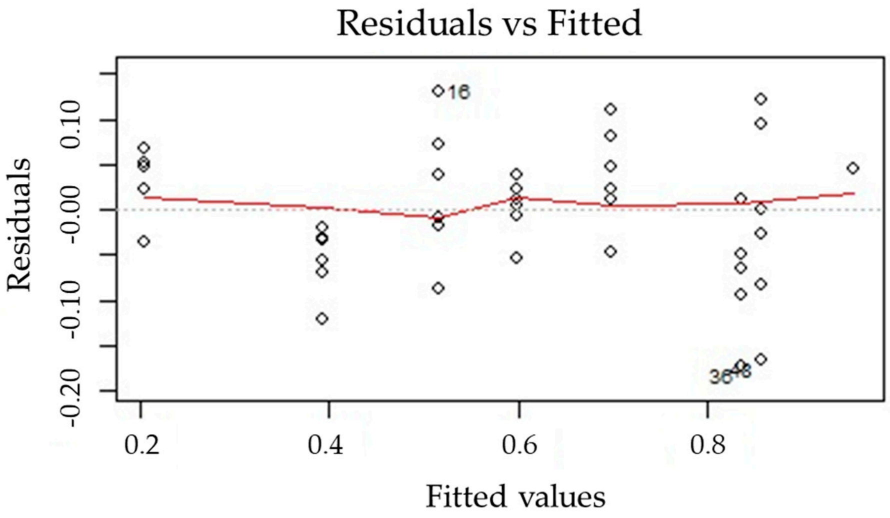

**Figure A2.** Residuals plotted against fitted values to visually assess homoscedasticity of the residuals of the fitted polynomial function for the temperature-induced dose component model. The straight red line means the point clustering shows no particular trend and the residuals could be considered homoscedastic.

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