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Studies into Fungal Decay of Wood In Ground Contact—Part 1: The Influence of Water-Holding Capacity, Moisture Content, and Temperature of Soil Substrates on Fungal Decay of Selected Timbers

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Abstract: This article presents the results from two separate studies investigating the decay of wood in ground contact using adapted versions of laboratory-based terrestrial microcosm (TMC) tests according to CEN/TS 15083-2:2005. The first study (A) sought to isolate the effect of soil water-holding capacity (WHC_{soil} [%]) and soil moisture content (MC_{soil} [%WHC_{soil}]) on the decay of five commercially important wood species; European beech (*Fagus sylvatica*), English oak heartwood (*Quercus robur*), Norway spruce (*Picea abies*), Douglas-fir heartwood (*Pseudotsuga menziesii*), and Scots pine sapwood (*Pinus sylvestris*), while keeping soil temperature (T_{soil}) constant. Combinations of soil mixtures with WHC_{soil} of 30%, 60%, and 90%, and MC_{soil} of 30%, 70%, and 95%WHC_{soil} were utilized. A general trend showed higher wood decay, measured in oven-dry mass loss (ML_{wood} [%]), for specimens of all species incubated in soils with WHC_{soil} of 60% and 90% compared to 30%. Furthermore, drier soils (MC_{soil} of 30 and 70%WHC_{soil}) showed higher ML_{wood} compared to wetter soils (95%WHC_{soil}). The second study (B) built on the first's findings, and sought to isolate the effect of T_{soil} and MC_{soil} on the decay of European beech wood, while keeping WHC_{soil} constant. The study used constant incubation temperature intervals (T_{soil}), 5–40 °C, and alternating intervals of 10/20, 10/30, and 20/30 °C. A general trend showed drier MC_{soil} (60%WHC_{soil}), and T_{soil} of 20–40 °C, delivered high wood decay (ML_{wood} > 20%). Higher MC_{soil} (90%WHC_{soil}) and T_{soil} of 5–10 °C, delivered low wood decay (ML_{wood} < 5%). Alternating T_{soil} generally delivered less ML_{wood} compared to their mean constant T_{soil} counterparts (15, 20, 25 °C). The results suggest that differences in wood species and inoculum potential (WHC_{soil}) between sites, as well as changes in MC_{soil} and T_{soil} attributed to daily and seasonal weather patterns can influence in-ground wood decay rate.

Keywords: in-ground wood decay; CEN/TS 15083-2:2005; soil water-holding capacity; soil moisture content; soil temperature

1. Introduction

Wood is one of the oldest raw materials used worldwide. As a construction material, it is used in a variety of manners, both indoors and outdoors. Due to its renewable and biodegradable properties, wood is becoming increasingly important when considering more environmentally friendly and sustainable construction materials. However, being renewable and biodegradable also poses considerable challenges to its utilization, requiring design measures to prevent degradation and extend service-life [1].

Wooden components are subjected to in-service factors causing decay that leads to a loss in functional performance (serviceability) or structural resistance. Outdoor wooden components are subjected to a variety of biotic and abiotic degradation factors. Wood used outdoors, in-ground contact, is especially prone to factors linked to accelerated degradation, due in-part to the permanent to semipermanent exposure to moisture (abiotic) and its role in the physiological requirements of wood-decaying fungi (biotic) [2]. Spores of wood decay fungi are ubiquitous and can be encountered in use situations all over the world, even in the harsh, subfreezing conditions of Antarctica [3]. Due in-part to ubiquity, wood decaying fungi are considered the most important biotic influencer to in-ground wood decay in the absence of termites and a water body which can host marine borers [4].

Important considerations for the successful proliferation of wood-decaying fungi include a carbon substrate, moisture, temperature, and oxygen [5,6]. Brown-, white-, and soft-rot fungi, can all be found on wood utilized in-ground, but these decay types can vary significantly, not only in frequency and spatial distribution, but also in combinations from one site to the next [7,8], and with decay progress [9,10].

Wood decay strongly depends on the decay type, whereby soft-rot, is considered to develop more slowly than white- and brown-rot [11]. Decay rate is also dependent on the respective physiological requirements of the decay types present. Soft-rot seems to be able to cope with high soil moisture content (MC_{soil}) better than brown- and white-rot fungi, and continues to remain active over a broader temperature range (T_{soil}) compared to brown- and white-rot fungi [7,12,13]. These varying requirements for optimum decay activity provided the basis for testing the effect of varying abiotic, soil-level variables, and their effect on wood decay (ML_{wood}).

Semifield, terrestrial microcosm (TMC) experiments were designed to mimic conditions found outdoors and were first used in the 1970s to investigate wood durability. During this time, such experiments were carried out without much standardization and were proven difficult to reproduce [14,15]. The advent of a soil water-holding capacity (WHC_{soil}) and MC_{soil} parameter within these experiments made for a noticeable leap forward in the standardization and reliability of inferred results [16,17]. Brischke and Wegener [18] investigated soil-wood moisture diffusivity over a 3-week trial period using soil substrates of various WHC_{soil} and MC_{soil} in TMC experiments. The study found that the lower the WHC_{soil}, the higher the MC_{wood} for the same MC_{soil}. This means soils with high WHC_{soil}, but low MC_{soil}, deliver less plant-available water (for decay organisms) than soil with WHC_{soil} at the same MC_{soil} [13]. However, the effect on wood decay is also dependent on the soil's inoculum potential, i.e., the activity level of the soil's microorganism community under specific moisture conditions. The standard CEN/TS 15083-2:2005 [19] requires WHC_{soil} of 20–60%, so as to standardize soil decay activity and to bring about consensus in wood durability ratings delivered by different studies. Soils with excessive decay activity (i.e., WHC_{soil} > 60%) will create bias in wood decay and durability ratings. To reduce WHC_{soil}, silica sand can be added to 'dilute' the inoculum potential to within WHC_{soil} of 20–60%. CEN/TS 15083-2:2005 [19] also requires MC_{soil} to be fixed at 95% of the WHC_{soil} (i.e., $\%WHC_{soil}$), while T_{soil} be fixed at 27 °C to isolate soft-rot fungal activity. The purpose of isolating soft-rot in unsterile soil tests is to complement pure fungal culture tests CEN/TS 15083-1:2005 [20] and also serve to recreate and rapidly test wood under conditions found outdoors in ground contact. These tests also complement field tests such as EN 252:2015 [21] and AWPA E7-15 [22]. However, conditions required for CEN/TS 15083-2:2005 [19] are not always representative and realistically comparable to outdoor in-ground conditions. Soil can be drier than $95\%WHC_{soil}$ and cooler than 27 °C for many months of the year, giving way to the proliferation of other soil-inhabiting microorganisms which could be more aggressive than soft-rot fungi.

Wood used in ground contact is subject to temperature fluctuations both above and below the soil surface. Wells and Boddy [23] tested the effect of temperature on wood decay and found that decay was higher at 25 °C compared to 10 °C. The tests used unsterile soil in petri dishes with wood specimens placed on top of the soil (on-ground decay). Other studies such as Risch et al. [24] and

Finér et al. [25], found soil temperature, and to a lesser extent, soil phosphorous concentration and available nitrogen, to be the best explanatory variables for the differences in wood decay between sites.

To investigate the effect of the abiotic, soil-level variables on the durability of wood used in ground contact, TMC experiments according to CEN/TS 15083-2:2005 [19] were undertaken in two separate studies: Study (A) examined the effect of (1) WHC_{soil} and (2) MC_{soil} on decay progress while keeping (3) T_{soil} constant. Study (B) kept examined the effect of (2) MC_{soil} and (3) T_{soil} while keeping (1) WHC_{soil} constant.

Software packages such as TimberLife [26] have developed a means towards modeling in-ground wood decay progression, and by extension durability and service-life. Durability and service-life show a clear link through the overlapping of data requirements used in these study fields [27]. The service-life of a product or component incorporates the concept of durability, but with additional information relating to usable lifespan. Part 2 of this research article series seeks to use a 'dosimeter' approach in modeling of in-ground wood decay [28]. Originally developed for aboveground wood, a dose–response approach will be applied to the obtained data sets.

2. Materials and Methods

2.1. Standard Test Requirements

Due to the similarity in methodology of study (A) and study (B), the following section regarding experimental methods is presented as relevant to both. Where necessary, differences in experimental methods are distinguished using capital lettering, study (A), or study (B). If relevance to (A) or (B) is not stipulated, the methodology applies to both.

Terrestrial microcosms (TMCs) in accordance with CEN/TS 15083-2:2005 [19] were utilized in semifield experiments. The standard stipulates that a natural topsoil or a fertile loam-based horticultural soil substrate is used, with pH 6–8 and no additives. The soil should have a WHC_{soil} of 20–60%, MC_{soil} equal to 95%WHC_{soil}, and the test should be conducted in a dark, climate-controlled room set to a temperature of 27 °C and relative humidity of 65%.

2.2. Preparation of Terrestrial Microcosms (TMC)

2.2.1. Soil Substrates

The basis of the substrate was a horticultural compost produced at the forest botanical garden at the University of Göttingen's North Campus. The compost comprised fallen leaves and cuttings from grass and trees. Soil was passed through a sieve with nominal aperture size of 8.5 mm. WHC_{soil} was then determined according to the 'cylinder sand bath method' according to ISO 11268-2 [29]. To lower the WHC_{soil} of the base compost substrate, silica sand (0–0.2 mm grain size) was added. Study A used substrates with WHC_{soil} of 30%, 60%, and 90%, while study B only used substrates with WHC_{soil} of 60%.

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

Soil samples of 50–90 g (depending on the soil density) were taken for determining the soil moisture content (MC_{soil}). Three replicate samples were taken, weighed to the nearest 0.01 g, oven-dried at 103 °C for 24 h, and weighed again. MC_{soil} was calculated according to Equation (1) below.

$$MC_{soil} = \left(\frac{m_w - m_0}{m_0} \right) \times 100 \quad (1)$$

where MC_{soil} is the soil moisture content [%]; m_w is the wet soil mass [g]; m_0 is the oven-dry soil mass [g].

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

Soil was inserted into polyethylene cylinders 10 cm long with 4 cm diameter. The bottoms of the cylinders were covered with a fine polymer grid and filter paper (MN 640 W 70 mm). All cylinders

were filled with soil to a height of 5–7 cm and saturated in an 8 cm high water bath for 3 h. After the saturation period, the cylinders were placed on a water saturated sand bath for 2 h to allow unbound water within the soil-filled cylinders to drain to reach the equivalent of field capacity. The soil samples were then weighed wet, as well as after oven-drying at 103 ± 2 °C for 24 h. WHC_{soil} [%] was calculated according to Equation (2) below.

$$WHC_{soil} = \left(\frac{m_s - m_0}{m_0}\right) \times 100 \quad (2)$$

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

2.2.4. Preparation of Mixed Soil Substrates

To mix the different soil substrates of compost and sand to the predetermined WHC_{soil} of 30%, 60%, and 90%, the WHC_{soil} of soils mixed in incremental ratios based on oven-dry mass was first determined. where WHC_{soil} is the target water-holding capacity of the soil mixture [%]; x is the fraction of sand substrate in the total soil mixture based on oven-dry mass [%]; R^2 is the coefficient of determination between actual and predicted values.

Table 1 below shows the incremental soil mixtures used to establish a WHC_{soil} regression equation for the substrates sand and compost. To prepare mixed soil substrates for testing WHC_{soil}, Equation (3) below was used.

$$m_{x,\,wet} = m_{total,\,dry} \times \left(\frac{x}{100}\right) \times \left(1 + \frac{MC_x}{100}\right) \quad (3)$$

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

A regression between the incremental mixing ratios of the two substrates sand and compost and their resulting WHC_{soil} was determined. Equation (4) below shows the regression relationship for WHC_{soil} of the two substrates used to define the mixture percentages to attain mixed soil substrates with WHC_{soil} of 30%, 60%, and 90% for study (A), while Equation (5) below shows the regression relationship for WHC_{soil} for study (B) to attain mixed soil substrates with WHC_{soil} of 60%. where WHC_{soil} is the target water-holding capacity of the soil mixture [%]; x is the fraction of sand substrate in the total soil mixture based on oven-dry mass [%]; R^2 is the coefficient of determination between actual and predicted values.

Table 1 below shows the output from computations using Equations (4) and (5).

$$WHC_{soil} = -0.0029x^2 - 0.4501x + 104.35 \quad R^2 = 0.9961 \quad (4)$$

$$WHC_{soil} = -0.0004x^2 - 0.6796x + 102.19 \quad R^2 = 0.9914 \quad (5)$$

where WHC_{soil} is the target water-holding capacity of the soil mixture [%]; x is the fraction of sand substrate in the total soil mixture based on oven-dry mass [%]; R^2 is the coefficient of determination between actual and predicted values.

Table 1. Mixing ratios of soil substrates for WHC_{soil} of mixed soil substrates. Percentage is based on the oven-dry soil mass [g].

	Resultant WHC_{soil} [%]										
(A): Equation (4)	104	95	88	81	74	67	60	53	45	37	30
(B): Equation (5)	102	99	94	88	81	74	66	58	49	40	30
Percentage compost [%]	100	90	80	70	60	50	40	30	20	10	0
Percentage sand [%]	0	10	20	30	40	50	60	70	80	90	100

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

Once the soil mixtures with target WHC_{soil} of 30%, 60%, and 90% were attained, three MC_{soil} were decided on for study (A); equal to 30, 70 and 95%WHC_{soil}. Two MC_{soil} were decided on for study (B); equal to 60 and 90%WHC_{soil}. Distilled water was added to the soil mixtures to reach MC_{soil} equal to 30, 70 and 90%WHC_{soil}, shown here as $MC_{soil,target}$ [%]. Therefore, distilled water was added to reach $MC_{soil,target}$ as shown below in Table 2. Equation (6) below was used to calculate the mass [g] in distilled water required to add to the soil mixture to reach $MC_{soil,target}$. If the soil was too moist to start with, the soils were placed in drying ovens set to 30 °C to dry out until the $MC_{soil,target}$ was reached. To account for losses in MC_{soil} resulting from fungal activity and evaporation, rewetting to $MC_{soil,target}$ occurred once per week throughout the 16-week incubation period.

Table 2. Combinations of soil mixtures prepared for use in studies (A) and (B).

Study	WHC_{soil} [%]	MC_{soil} [%WHC_{soil}]	$MC_{soil,target}$ [%]
(A)	30	30	9
(A)	30	70	21
(A)	30	95	29
(A)	60	30	18
(A)	60	70	42
(A)	60	95	57
(A)	90	30	27
(A)	90	70	63
(A)	90	95	86
(B)	60	60	36
(B)	60	90	54

$$m_{water} = \left(\frac{MC_{soil,target} - MC_{soil,current}}{100} \right) \times m_{total,\ dry} \quad (6)$$

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

2.2.6. Soil Temperature (T_{soil}) Control

For study (A), TMC boxes were stored in a temperature-controlled room set to a temperature of 20 ± 2 °C, while for study (B), climate chambers were used to incubate the TMCs and simulate differences in T_{soil}. In total, eight constant T_{soil} and three alternating T_{soil} were investigated. Constant T_{soil} rose in 5 °C intervals from 5 to 40 °C, while alternating T_{soil} cycled to 10/20, 10/30, and 20/30 °C. Temperature was changed once every 7 days for TMCs of alternating T_{soil}, meaning that a full cycle of alternation lasted 14 days, or 2 weeks. Two TMCs per T_{soil} were prepared. In total, 22 TMCs were prepared; one TMC per T_{soil} (eight fixed, three alternating), per MC_{soil} (60 and 90%WHC_{soil}). Relative humidity of 65% was maintained in all climate chambers.

2.2.7. Preparation and Exposure of Wood Specimens

In study (A) European beech (*Fagus sylvatica* L.), Norway spruce (*Picea abies* Karst.), Scots pine sapwood (*Pinus sylvestris* L.), English oak heartwood (*Quercus robur* L.), and Douglas-fir heartwood (*Pseudotsuga mensziesii* Franco.) were used. Specimens of 5 × 10 × 100 (ax.) mm^3 were prepared, in accordance with CEN/TS 15083-2:2005 [19]. Kiln-dried boards (>60 °C) were conditioned to wood moisture content (MC_{wood}) of 12 ± 2%. Specimens were then prepared from planed strips of the boards, with a cross-section of 10 ± 0.1 mm × 5 ± 0.1 mm. Annual rings were orientated 90 ± 15° to the broad face of the specimen (i.e., 10 mm face). Transverse cuts of the cross-section delivered sharp edges and a

fine-sawn finish to the end-grain surface, with a final specimen length of 100 ± 1 mm. All specimens were free from defects such as cracks, decay, and discolouration.

After specimen preparation, all specimens were oven-dried at 103 °C for 24 h and weighed for oven-dry mass to the nearest 0.001 g. Prior to soil exposure, all specimens were again conditioned to MC_{wood} of 12 ± 2% (confirmed by Equation (7) below) and buried 4/5 of their length into the soil substrate with 120 specimens per TMC box. In total, 1080 test specimens were used; eight replicate specimens for each of the five wood species, three specimen removal intervals (8, 12, 16 weeks), and nine different soil conditions. After soil exposure, specimens were removed, cleaned of remaining soil, and again oven-dried at 103 °C for 24 h. Specimens were then weighed again to the nearest 0.001 g with oven-dry wood mass loss (ML_{wood}) calculated according to Equation (8) below. Mean ML_{wood} and standard deviation of mean ML_{wood} was calculated according to Equations (9) and (10) below.

$$MC_{wood} = \left(\frac{m_3 - m_2}{m_2}\right) \times 100 \quad (7)$$

where MC_{wood} is the wood moisture content [%]; m_3 is the wood specimen's mass after TMC exposure [g]; m_2 is the wood specimen's oven-dry mass after TMC exposure [g].

Oven-dry mass loss (ML_{wood}) and wood was calculated according to Equation (8) below.

$$ML_{wood} = \left(\frac{m_1 - m_2}{m_1}\right) \times 100 \quad (8)$$

where ML_{wood} is the wood specimen's oven-dry mass loss [%]; m_1 is the wood specimen's oven-dry mass before TMC exposure [g]; m_2 is the wood specimen's oven-dry mass after TMC exposure [g].

Mean ML_{wood} was calculated according to Equation (9) below.

$$mean\ ML_{wood} = \frac{1}{n}\sum_{i=1}^{n} x_i \quad (9)$$

where $mean\ ML_{wood}$ is the arithmetic mean of the oven-dry mass loss of the sample population [%]; x_i is the oven-dry mass loss (ML_{wood}) of each individual wood specimen in the sample population [%]; n is the total number of wood specimens in the sample population.

Standard deviation of mean ML_{wood} was calculated according to Equation (10) below.

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \overline{x})}{n-1}} \quad (10)$$

where s is the standard deviation of the sample population; x_i is the oven-dry mass loss (ML_{wood}) of each individual wood specimen in the sample population [%]; $\overline{x}$ the mean oven-dry wood mass loss (mean ML_{wood}) of the sample population [%]; n is the total number of wood specimens in the sample population.

In study (B), European beech wood specimens of 5 × 10 × 100 (ax.) mm^3 were prepared in the same manner as study (A), i.e., in accordance with CEN/TS 15083-2:2005 [19]. Specimens were also buried 4/5 of their length into the soil substrate, but rather with 80 specimens per TMC. A subset of 10 replicate specimens was removed every 2 weeks. In total, eight exposure intervals, 11 T_{soil} (eight fixed, three alternating), and two MC_{soil} (60 and 90%WHC_{soil}), delivered a total of 1760 beech wood specimens used in the study.

3. Results and Discussion

3.1. Impact of WHC_{soil} and MC_{soil} on Fungal Decay (Study A)

The mean ML_{wood} of all five wood species used in study (A) during 16 weeks of incubation is shown in Figure 1. Oak seemed the most resilient to high ML_{wood} of all tested wood species with

the maximum mean ML_{wood} not exceeding 20%. When considering mean ML_{wood} across all soil conditions measured at the 16 week incubation interval, wood species with low durability (in ground contact) such as beech and Scots pine sapwood [30] showed the highest mean ML_{wood}, i.e., 18% and 17%, respectively (Table 3). All species generally showed higher mean ML_{wood} in the soil mixtures with WHC_{soil} of 60% and 90% compared to 30%. This was attributable to the high percentage of silica sand constituting almost 100% of the soil mixtures with WHC_{soil} of 30%, which showed a lower presence of microorganisms compared to the soil mixtures with WHC_{soil} of 60 and 90%. Although only limited ML_{wood} occurred in soils with WHC_{soil} of 30%, the result remains important nonetheless, to gain an understanding of wood decay across a broad range of WHC_{soil}. Soil particle size distribution is an underlying determinant of WHC_{soil} [31]. However, other sandy soil types with comparable particle size distribution and WHC_{soil} can possess a different (and potentially higher) wood decay potential than the sandy soils used in this study. The sand used in this study was purchased from a supplier and packaged in 25 kg bags. This means the sand was subject to industrial processes such as sieving for consistent particle size distribution (0–0.2 mm grain size) and drying to ensure consistent packaging quantities. This would naturally result in a lower inoculum potential compared to undisturbed sandy soils.

Soils with MC_{soil} of 95%WHC_{soil} showed consistently lower ML_{wood} than drier soils with MC_{soil} of 30 and 70%WHC_{soil}. Increased moisture also stimulates microbial activity; however, decay was impaired once an optimal level of MC_{soil} and MC_{wood} was exceeded. Full mean ML_{wood} data with accompanying standard deviation can be found in Appendix A. Tables A1–A5 in Appendix A are presented in order of wood species.

Table 3. Mean oven-dry mass loss (ML_{wood} [%]; $n = 8$) and total mean oven-dry mass loss (ML_{wood}* [%]; $n = 72$) of European beech (beech), English oak heartwood (oak), Norway spruce (spruce), Douglas-fir heartwood (d-fir), and Scots pine sapwood (pine) wood specimens after 16 weeks incubation under soil conditions with water-holding capacity (WHC_{soil}) of 30%, 60%, and 90%, and soil moisture content (MC_{soil}) of 30, 70, and 95%WHC_{soil}, at constant soil temperature (T_{soil}) of 20 ± 2 °C.

	ML_{wood} [%] per Soil Condition WHC_{soil}[%]/MC_{soil}[%WHC_{soil}]									
Species	**30/30**	**30/70**	**30/95**	**60/30**	**60/70**	**60/95**	**90/30**	**90/70**	**90/95**	**ML_{wood}* [%]**
Beech	5.45	6.15	4.28	28.26	23.09	9.27	33.85	46.98	7.82	18.35
D-fir	1.03	1.53	1.50	17.04	5.32	0.51	42.09	4.41	0.92	8.26
Oak	4.32	5.88	4.50	9.29	18.95	1.23	10.97	17.69	1.93	8.31
Spruce	0.76	1.78	1.24	25.54	10.07	0.20	50.61	9.65	0.84	11.29
Pine	2.10	3.46	3.18	46.66	17.81	2.66	58.24	14.54	2.44	16.79

Besides a source of fungal inoculum itself (mycelium or spores), Zabel and Morrell [32], list four critical requirements for fungal growth in wood, namely, a source of free or unbound water, favorable temperatures (approximately 0–42 °C), atmospheric oxygen, and a digestible carbon substrate. In addition to these requirements comes the added complexity of understanding which specific fungi types are active throughout various ranges of these critical requirements, and if any of these requirements (reagents) were only available in limited quantity. Extensive research has already been conducted to illustrate that different soils in different locations can deliver different dominating decay rates and types [8,33–38].

While this study used one soil characteristic, WHC_{soil}, as a metric to describe the soil's capillarity or moisture retention ability, the broader concept of pedogenesis (soil formation or development) begins to show relevancy for outdoor, in-field wood decay testing. Soil genesis describes how a soil, in all of its layers, came to be in its present state. Environmental factors in parent material (underlying geology), climate, biota (organisms), topography, and time, operate through soil processes of additions, losses, translocations, and transformations to form soils [39]. This means that soils from different locations, and soil layers (horizons) within a single soil profile can show varying characteristics in

their physical, biological, and chemical composition. All of these can influence microorganism decay activity. However, within this study's controlled environment, WHC_{soil}, MC_{soil}, and wood species still showed promise as prediction variables to ML_{wood}, due simply to the role of moisture in fungal wood decay, that is without moisture, wood decay ceases.

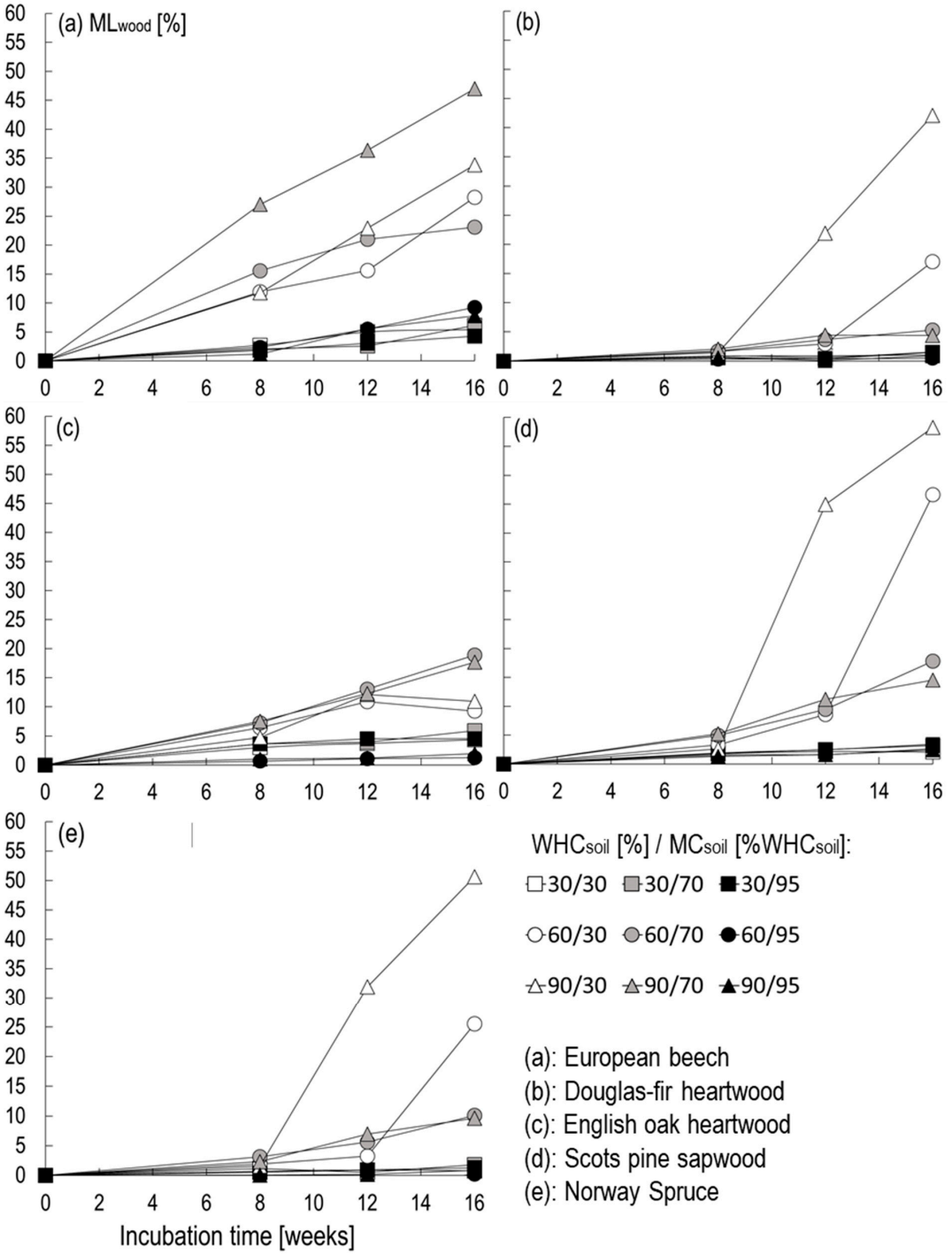

Figure 1. Mean oven-dry mass loss (ML_{wood}) of (**a**) European beech, (**b**) Douglas-fir heartwood, (**c**) English oak heartwood, (**d**) Scots pine sapwood, and (**e**) Norway spruce wood specimens incubated for 16 weeks in soil conditions with water-holding capacity (WHC_{soil}) of 30, 60, and 90 [%], and soil moisture content (MC_{soil}) of 30, 70, and 95 [%WHC_{soil}].

Oxygen availability in soil should also be kept in mind when considering moisture availability. Under conditions of high MC_{soil}, oxygen availability decreases, since the soil pore spaces become filled with liquid, which in-turn slows wood decay. Examinations of wooden foundation piles have confirmed a protective effect of high soil moisture levels. In waterlogged, anaerobic soils, wood decay is found to progress slowly through wood-decaying bacteria while aggressive wood-decaying fungi are suppressed [40,41].

3.2. Impact of T_{soil} and MC_{soil} on Fungal Decay (Study B)

3.2.1. Constant T_{soil}

The mean ML_{wood} of 10 beech wood specimens for every T_{soil} and every 2-week specimen removal interval over the 16-week incubation period is shown in Figure 2. At constant T_{soil}, TMCs with lower MC_{soil} (60%WHC_{soil}, Figure 2a,c below) delivered higher ML_{wood} than those with higher MC_{soil} (90%WHC_{soil}, Figure 2b,d below). Lower MC_{soil} in combination with T_{soil} of 15–40 °C were favorable decay conditions (ML_{wood} > 20%), with optimum ML_{wood} occurring at 35 °C. However, 35 °C also showed the highest standard deviation of 13.9% (Appendix A: Table A6).

Higher MC_{soil} in combination with low T_{soil} of 5–10 °C showed unfavorable decay conditions (ML_{wood} < 5%), where temperature alone could not be held accountable for the inhibited decay, with increased MC_{soil} also contributing [42]. For higher MC_{soil}, the optimum T_{soil} was 25 °C with ML_{wood} at 16.0% after 16 weeks of incubation. This value corresponded to ML_{wood} at 10 °C for specimens exposed to lower MC_{soil}. Interestingly, 40 °C seemed to show consistently higher ML_{wood} compared to 25 °C throughout the early and middle incubation periods, however 25 °C ultimately showed higher ML_{wood} after 16 weeks.

For both MC_{soil} conditions, ML_{wood} also increased with incubation time. Generally, for both MC_{soil} conditions tested, ML_{wood} increased with T_{soil}. However, some T_{soil} intervals showed exceptions to this trend, such as 15 and 35 °C for MC_{soil} of 90%WHC_{soil}. It was assumed that problems related to ventilation within the climate chamber led to inconsistent results here.

Previous studies investigating in-ground wood decay have confirmed an interactive relationship between MC_{soil} and T_{soil} on wood decay [42,43]. Soil moisture has the potential to alter the response of fungal growth to warming, meaning that wood decay can be inhibited if soil is too wet or too dry [44]. Elevated temperature (3 °C above ambient of 15 °C) did not significantly increase wood decomposition rate alone or in combination with increases in MC_{wood} and MC_{soil} [42]. However, drying (of both soil and wood), results in a decreased wood decay rate [42], coincidently illustrated for 15 °C with MC_{soil} of 90%WHC_{soil}, where excessive ventilation (drying) could be to blame.

Figure 2c,d plotted ML_{wood} against T_{soil} as a function of incubation period (2-16 weeks), for both lower and higher MC_{soil}. From this, the effect that changes in T_{soil} had on ML_{wood} could be deduced. Decay rate can increase more drastically with an increase in T_{soil} later in the incubation period compared to earlier in the incubation period. This can be seen from the steeper gradient of ML_{wood} with increasing incubation period, and is illustrated clearly in Figure 2c, where clear differences in ML_{wood} are discernible.

For MC_{soil} of 60%WHC (Figure 2c above), the effect that an increase in the T_{soil} from 5 to 35 °C had on ML_{wood} could be seen by comparing ML_{wood} at the exposure intervals of 4 and 16 weeks. After 4 weeks, increasing T_{soil} by 1 °C, ML_{wood} increased by 0.6%; towards the end of the study period, after 16 weeks, ML_{wood} changed by 1.0%. It can be assumed that the increased rate of decay is related to the development of wood-decaying microorganisms. This assumption is consistent with the observation of Eaton and Hale [45], that at the beginning of exposure there was a comparatively low mass of microorganisms in the test soil as well as in the wooden test specimens. After an initial phase of fungal colonization, decay of the wooden substrate began. Changes in temperature therefore have a greater effect the further decay progresses [46].

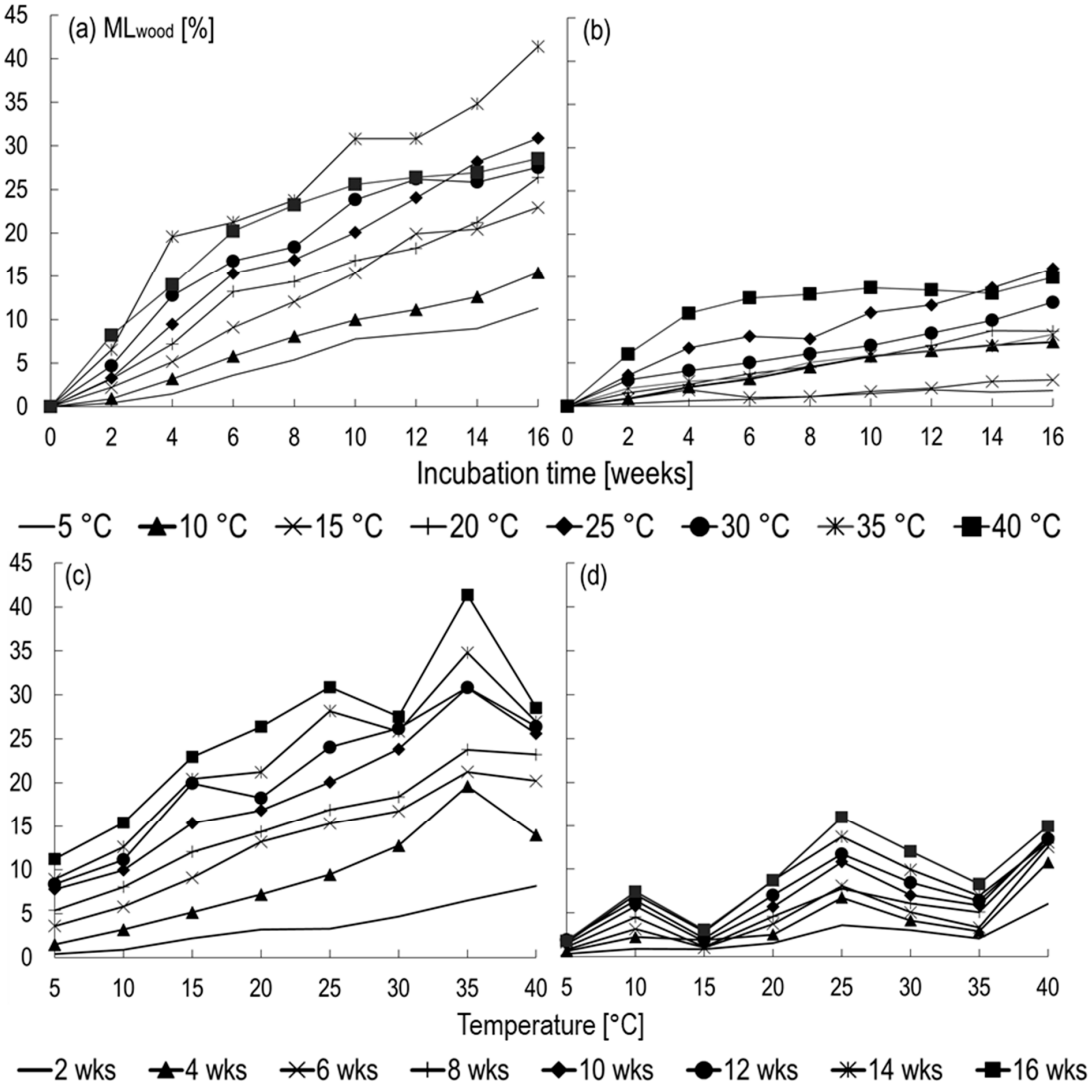

Figure 2. Mean oven-dry mass loss (ML_{wood}) of European beech wood specimens incubated for 16 weeks at constant soil temperature (T_{soil}) with soil water-holding capacity (WHC_{soil}) of 60% and soil moisture content (MC_{soil}) of 60%WHC_{soil} (**a**), and 90%WHC_{soil} (**b**). Mean oven-dry mass loss (ML_{wood}) of beech wood specimens plotting against increasing soil temperature (T_{soil}) for a specified incubation period (# wks), incubated in soil with water-holding capacity (WHC_{soil}) of 60% and soil moisture content (MC_{soil}) of 60%WHC_{soil} (**c**), and MC_{soil} of 90%WHC_{soil} (**d**).

For a given fungi species (and isolate), above the lower T_{soil} decay activity limit, the "reaction speed-temperature (RST) rule" begins to take effect, which states that in a certain temperature range, increasing the temperature by about 10 °C, enzyme activity (and therefore decay rate) runs faster by a factor of 2–4. Frequently, the optimum lies, depending on the species (and isolate) between 20 and 40 °C [4,47].

For lower MC_{soil} (Figure 2c above), increasing T_{soil} from 5 to 15 °C increased ML_{wood} by a factor of 1.97 (10 weeks incubation) to 5.42 (2 weeks incubation) and thus a factor of 2.0 for almost all incubation intervals of this T_{soil} range was exceeded. When T_{soil} was increased from 10 to 20 °C, the factor increases only exceeded 2.0 for the first three incubation intervals (2, 4, and 6 weeks). The RST rule was thus only confirmed for lower T_{soil} and especially at the beginning of the incubation period.

A review of the RST rule for MC_{soil} of 90%WHC_{soil} showed an overall more heterogeneous picture due to the peaks at 25 and 40 °C and low ML_{wood} values at 15 °C (Figure 2d above). Consequently, T_{soil} increase from 15 to 25 °C, resulted in ML_{wood} increasing by a range of factors, starting at 3.55

(4 weeks incubation) to 7.92 (6 weeks incubation). With T_{soil} increased from 30 to 40 °C, the factor only exceeded 2.0 for the incubation intervals of 4–8 weeks. The low ML_{wood} of T_{soil} at 15 °C, did indeed confirm the RST rule for T_{soil} interval from 15 to 25 ° C, but was only of limited significance due to low ML_{wood} at 15 °C causing an overrated ML_{wood} at higher T_{soil}. Overall, it was found that the RST rule could only be confirmed for individual T_{soil} intervals and therefore could not be confirmed generally for both MC_{soil} ranges. It should also be mentioned that ML_{wood} was used to test the validity of the RST rule because it was assumed that ML_{wood} was proportional to fungal enzyme activity and therefore wood decay rate. However, fungal enzyme activity and wood decay rate should not be used synonymously since many factors determine wood decay rate as measured by oven-dry mass loss, such as wood species, fungal community composition, fungal community succession, and MC_{soil}, to mention but a few. More information regarding various factors influencing wood decay and service-life can be found in Marais et al. [48]. Full mean ML_{wood} data with accompanying standard deviation for constant T_{soil} can be found in Appendix A: Tables A6 and A8.

3.2.2. Alternating T_{soil}

The test specimens in TMC with alternating T_{soil} showed a similar trend to those with constant T_{soil} conditions. ML_{wood} of test specimens exposed to MC_{soil} of 60%WHC_{soil} showed an influence from T_{soil} at the start of the test period, which became clearer throughout the course of the test (Figure 3a,c,e below). Here too, ML_{wood} after 16 weeks was greater than 20%, except for T_{soil} at 10/20 ° C with ML_{wood} of 19.4%. As with constant T_{soil}, ML_{wood} for MC_{soil} of 90%WHC_{soil} was considerably lower than for MC_{soil} of 60%WHC_{soil}. However, contrary to constant T_{soil}, no increase in ML_{wood} with increasing T_{soil} was detected. The alternating T_{soil} pair of 10/20 °C showed the highest ML_{wood}, but this was still low after 16 weeks (ML_{wood} < 10%). Problems related to the maintenance of temperature, humidity, and air movement within the climate chamber may be to blame for this (i.e., high evaporation between rewetting intervals). Full mean ML_{wood} data with accompanying standard deviation for alternating T_{soil} can be found in Appendix A; Tables A7 and A9.

3.2.3. Comparison: Constant vs. Alternating T_{soil}

Alternating T_{soil} (10/20, 10/30, 20/30 °C), delivered lower ML_{wood} compared to their mean constant T_{soil} counterparts (15, 20, 25 °C) regardless of MC_{soil} (Figure 3), but with the exception of 10/20 °C at higher MC_{soil} (Figure 3b below), which delivered higher ML_{wood} than its mean constant T_{soil} counterpart of 15 °C. These results correspond with previous findings concerning pure fungal cultures where alternating incubation temperatures rarely led to a higher fungal growth rate than a mean constant temperature counterpart [49]. Furthermore, indiscriminate temperature fluctuation across a defined temperature range was more indicative of a natural environment than alternating temperature aligned to the minimum and maximum of the defined range [50].

Fungal dormancy may also explain the decreased ML_{wood} when compared to its mean constant T_{soil} counterparts. Dormancy refers to a physiological state of fungal activity defined by strongly reduced respiration reflective of a form of resting, which does not contribute to turnover processes (i.e., wood decay and the organic matter in the soil). Once dormant, the requirements for reactivation are limited to rewetting and/or the addition of new organic material to the substrate [51]. However, since soil moisture was maintained at constant levels throughout all the TMC setups and organic material was in abundance, the decreased ML_{wood} was most likely the result of fungal respiration reacting to altered T_{soil}, which includes a lag period. Furthermore, the removal of specimens every 2 weeks made it difficult to understand the influence of a single T_{soil} interval in the alternating cycle, since T_{soil} was altered every week. Since a fungal characterization study also did not form part of this article, knowing the exact temperature and moisture boundaries (or curve) and subsequently stating which fungi groups were active, partially active, dormant, or dead, remains speculative.

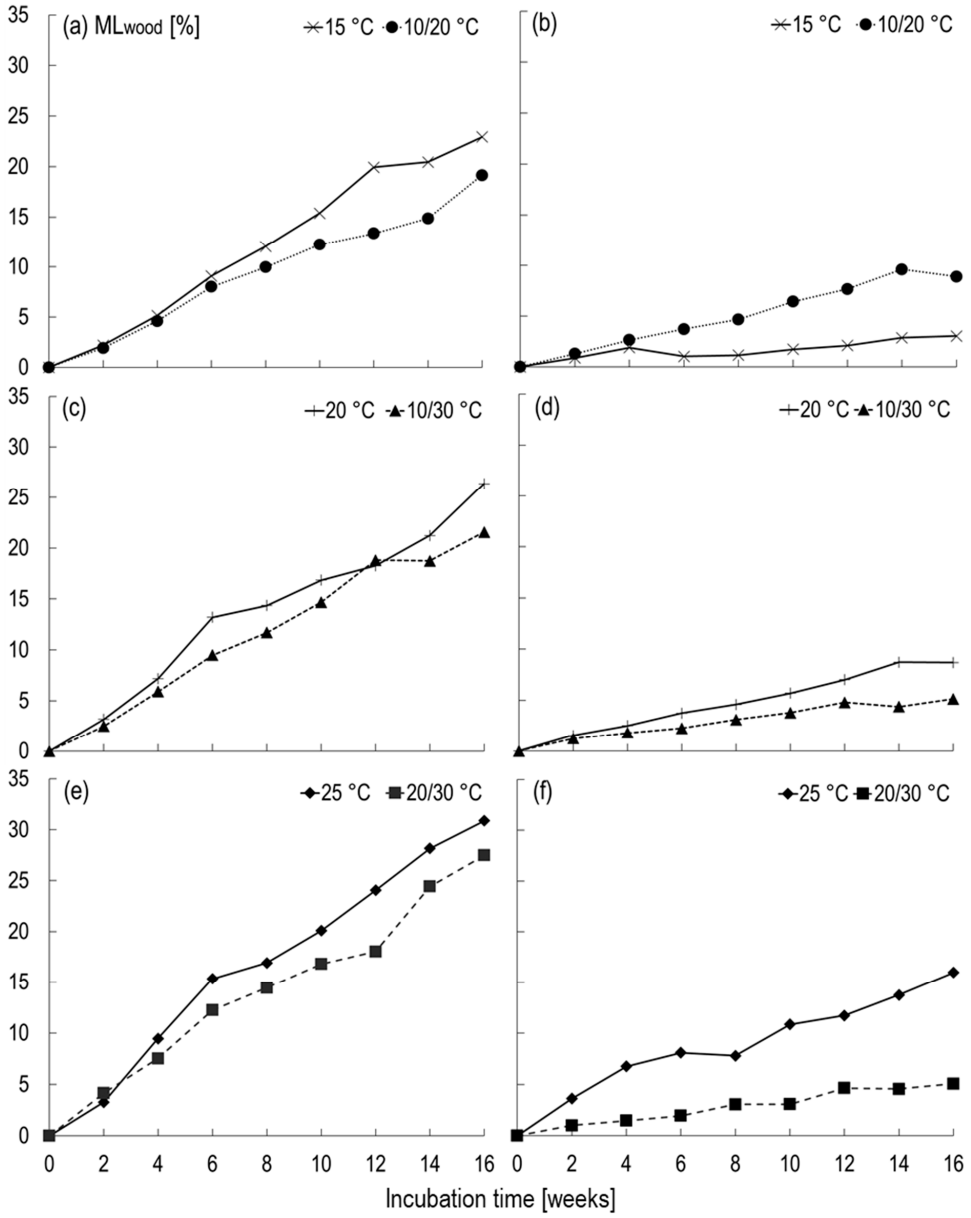

Figure 3. Comparisons of mean oven-dry mass loss (ML_{wood}) of beech wood specimens incubated at constant and alternating soil temperature (T_{soil}) with soil water-holding capacity (WHC_{soil}) of 60% and soil moisture content (MC_{soil}) of 60%WHC_{soil} (left panel: (**a**,**c**,**e**)), and 90%WHC_{soil} (right panel: (**b**,**d**,**f**)).

4. Conclusions

The studies presented in this article show a clear influence of WHC_{soil}, MC_{soil}, and T_{soil} on the decay of wood in soil contact. Fungal activity was either inhibited or promoted depending on the combination of these abiotic soil-level conditions. For all five wood species tested in study A, European beech, Douglas-fir heartwood, English oak heartwood, Scots pine sapwood, and Norway spruce, decreased ML_{wood} occurred under conditions of high MC_{soil} (i.e., MC_{soil} = 95%WHC_{soil}).

In study B, both T_{soil} and MC_{soil} showed an influence on the decay activity of soil-inhabiting microorganisms. Both abiotic factors MC_{soil} and T_{soil} influenced each other in such a way that wood decay increased or came to a standstill. Already at the beginning of the test period a reciprocal effect was noticed, where higher T_{soil} in combination with lower MC_{soil} resulted in an increased decay rate, while at low T_{soil}, especially in the wetter soil environment (90%WHC_{soil}), only slight decay took place. This trend continued over the entire trial period of 16 weeks.

Alternating T_{soil} conditions decreased wood decay activity of soil microorganisms compared to their corresponding constant T_{soil} counterparts. It was assumed that weekly T_{soil} changes required soil microorganisms to adapt to the altered environmental conditions, which impaired wood decay rate.

A graphical comparison of ML_{wood} after different exposure intervals showed that when using ML_{wood} as indicator, the reaction-speed temperature (RST) rule, which establishes a connection between T_{soil} and wood decay rate, could not be generally confirmed. When considering MC_{soil} of 60%WHC_{soil}, which was responsible for more favorable decay conditions, an increase in T_{soil} at the end of the trial period showed a stronger influence on increases of ML_{wood} compared to an earlier stage of the trial period. This indicates that an initial fungal settlement phase was required before T_{soil} increases could be linked to increases in wood decay rate. It would be of interest here to obtain a differentiated picture of the antagonistic and synergetic interactions between the microorganisms by demonstrating the organisms involved in wood decay. Inferences regarding decay severity can be made once the conditions surrounding microbial invasion of the wood substrate are understood (i.e., T_{soil}, WHC_{soil}, and MC_{soil}). Irrespective of the RST rule, this data is valuable nonetheless due to the frequent specimen removal interval throughout the 16-week incubation period and the range in T_{soil}, which can allow for further use in modeling the service-life of wood in ground contact. Responses of ML_{wood} to changes in T_{soil} at different stages of decay progress were therefore quantifiable in percentage of oven-dry mass loss (ML_{wood} [%]).

Advancements in wood service-life prediction have incorporated a distinction between biological factors causing degradation and structural effects on timber, and the structural response of timber to both loads and loss of resistance to loads due to decay [27,28,52]. Software packages such as TimberLife [26] have modeled decay progression of wood in ground contact by using indirect macroclimate data, such as that from the Scheffer Climate Index [53], coupled to 35 years of field trial data to develop regional wood decay rates, presented as a risk map for the entire continent of Australia. These are species-specific, which include mostly Australasian, and some prominent European and North American wood species. Other methodologies of modeling decay progression, such as dose–response, rather use wood microclimate data in MC_{wood} and T_{wood} (dose) to calculate the number of ideal expose days required for decay onset until ultimate failure of the wooden component to occur (response). The method uses a '0-4 limit-state' evaluation system to describe stages of decay progress as a function of decay depth and spatial distribution. In this case, the wood-and-soil microclimate is sought to be defined through the addition of soil-level variables as investigated in this article. Further differentiation between these two methodologies and the advantages and disadvantages of each can be expected in Part 2 of the article series.

The complexity of the relationship that the parameters T_{soil}, MC_{soil}, and WHC_{soil} have to one another and the wood decaying microorganisms that are active at various dose loads (i.e., combinations of WHC_{soil}, MC_{soil}, and T_{soil}) was evident. Additionally, Part 2 will present deeper statistical analyses into significant differences in ML_{wood} between these various dose loads.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Mean oven-dry mass loss (ML_{wood}) and (standard deviation) of eight European beech (*Fagus sylvatica* L.) wood specimens removed at incubation intervals of 8, 12, and 16 weeks under soil conditions with water-holding capacity (WHC_{soil}) of 30%, 60%, and 90%, and soil moisture content (MC_{soil}) of 30, 70, and 95%WHC_{soil}, at constant soil temperature ($Temp_{soil}$) of 20 ± 2 °C.

Soil Condition WHC_{soil}[%]/MC_{soil}[%WHC_{soil}]	Exposure Interval [Weeks]		
	8	12	16
30/30	2.73 (1.61)	5.02 (5.28)	5.45 (5.43)
30/70	2.06 (0.35)	2.59 (2.84)	6.15 (1.76)
30/95	1.83 (0.63)	3.08 (0.92)	4.28 (0.83)
60/30	11.97 (1.08)	15.61 (2.76)	28.26 (10.23)
60/70	15.59 (2.73)	21.01 (3.03)	23.09 (6.95)
60/95	2.35 (0.90)	5.54 (2.76)	9.27 (6.76)
90/30	11.75 (2.05)	22.92 (3.21)	33.85 (7.84)
90/70	27.03 (6.00)	36.38 (7.11)	46.98 (9.92)
90/95	1.18 (9.51)	5.56 (1.58)	7.82 (2.18)

Table A2. Mean oven-dry mass loss (ML_{wood}) and (standard deviation) of eight Douglas-fir (*Pseudotsuga mensziesii* Franco.) wood specimens removed at incubation intervals of 8, 12, and 16 weeks under soil conditions with water-holding capacity (WHC_{soil}) of 30%, 60%, and 90%, and soil moisture content (MC_{soil}) of 30, 70, and 95%WHC_{soil}, at constant soil temperature ($Temp_{soil}$) of 20 ± 2 °C.

Soil Condition WHC_{soil}[%]/MC_{soil}[%WHC_{soil}]	Exposure Interval [Weeks]		
	8	12	16
30/30	0.80 (0.12)	0.92 (0.22)	1.03 (0.27)
30/70	0.85 (0.14)	0.66 (1.56)	1.53 (0.65)
30/95	0.62 (0.25)	0.40 (0.85)	1.50 (0.86)
60/30	1.68 (0.53)	2.91 (1.13)	17.04 (12.57)
60/70	1.69 (0.54)	3.67 (0.66)	5.32 (5.06)
60/95	0.32 (0.31)	0.36 (0.66)	0.51 (0.37)
90/30	1.42 (0.64)	21.91 (8.70)	42.09 (9.63)
90/70	2.04 (0.51)	4.43 (1.73)	4.41 (1.85)
90/95	0.53 (0.34)	1.10 (0.57)	0.92 (0.36)

Table A3. Mean oven-dry mass loss (MLwood) and (standard deviation) of eight English oak (*Quercus robur* L.) wood specimens removed at incubation intervals of 8, 12, and 16 weeks under soil conditions with water-holding capacity (WHCsoil) of 30%, 60%, and 90%, and soil moisture content (MC_{soil}) of 30, 70, and 95%WHC_{soil}, at constant soil temperature ($Temp_{soil}$) of 20 ± 2 °C.

Soil Conditions WHC_{soil}[%]/MC_{soil}[%WHC_{soil}]	Exposure Interval [Weeks]		
	8	12	16
30/30	2.98 (0.14)	3.71(0.80)	4.32 (0.67)
30/70	3.66 (0.43)	3.94 (0.73)	5.88 (0.71)
30/95	3.65 (0.75)	4.52 (0.63)	4.50 (0.68)
60/30	6.42 (1.45)	10.87 (2.04)	9.29 (3.13)
60/70	7.25 (1.31)	13.07 (1.55)	18.95 (2.99)
60/95	0.65 (0.22)	1.07 (1.05)	1.23 (0.40)
90/30	4.75 (0.76)	12.14 (2.14)	10.97 (1.37)
90/70	7.53 (0.79)	12.31 (1.41)	17.69 (1.47)
90/95	1.00 (2.15)	1.21 (0.60)	1.93 (0.35)

Table A4. Mean oven-dry mass loss (ML_{wood}) and (standard deviation) of eight Scots pine (*Pinus sylvestris* L.) wood specimens removed at incubation intervals of 8, 12, and 16 weeks under soil conditions with water-holding capacity (WHC_{soil}) of 30%, 60%, and 90%, and soil moisture content (MC_{soil}) of 30, 70, and 95%WHC_{soil}, at constant soil temperature ($Temp_{soil}$) of 20 ± 2 °C.

Soil Condition WHC_{soil}[%]/MC_{soil}[%WHC_{soil}]	Exposure Interval [Weeks]		
	8	12	16
30/30	1.76 (0.19)	2.16 (0.49)	2.10 (0.18)
30/70	1.92 (0.29)	2.50 (1.16)	3.46 (0.56)
30/95	1.86 (0.47)	2.51 (0.42)	3.18 (1.69)
60/30	3.29 (0.41)	8.56 (4.64)	46.66 (7.76)
60/70	4.96 (0.58)	9.47 (0.90)	17.81 (5.57)
60/95	1.51 (0.61)	1.64 (3.45)	2.66 (0.56)
90/30	2.60 (0.36)	44.96 (15.16)	58.24 (4.26)
90/70	5.28 (1.08)	11.21 (1.72)	14.54 (1.33)
90/95	1.36 (0.37)	1.62 (0.37)	2.44 (0.27)

Table A5. Mean oven-dry mass loss (ML_{wood}) and (standard deviation) of eight Norway spruce (*Picea abies* Karst.) wood specimens removed at incubation intervals of 8, 12, and 16 weeks under soil conditions with water-holding capacity (WHC_{soil}) of 30%, 60%, and 90%, and soil moisture content (MC_{soil}) of 30, 70, and 95%WHC_{soil}, at constant soil temperature ($Temp_{soil}$) of 20 ± 2 °C.

Soil Condition WHC_{soil}[%]/MC_{soil}[%WHC_{soil}]	Exposure Interval [Weeks]		
	8	12	16
30/30	0.66 (0.32)	0.87 (0.67)	0.76 (0.16)
30/70	1.17 (1.77)	0.50 (0.18)	1.78 (0.60)
30/95	0.50 (0.24)	0.91 (0.41)	1.24 (0.48)
60/30	1.88 (0.30)	3.21 (1.24)	25.54 (12.09)
60/70	3.11 (1.50)	5.62 (1.68)	10.07 (5.62)
60/95	0.03 (1.18)	−0.182 (0.443)	0.20 (0.80)
90/30	1.53 (0.98)	31.92 (22.97)	50.61 (14.67)
90/70	2.33 (1.09)	6.96 (2.33)	9.65 (2.81)
90/95	0.05 (0.43)	0.18 (0.36)	0.84 (0.54)

Table A6. Mean oven-dry wood mass loss (ML_{wood}) and (standard deviation) of 10 European beech (*Fagus sylvatica* L.) wood specimens removed in 2-week intervals over 16 weeks of incubation under soil conditions with water-holding capacity (WHC_{soil}) of 60%, soil moisture content (MC_{soil}) of 60%WHC_{soil}, and constant soil temperature ($Temp_{soil}$).

Temp. [°C]	Exposure Interval [Weeks]							
	2	4	6	8	10	12	14	16
5	0.41 (0.13)	1.49 (0.34)	3.59 (0.55)	5.38 (0.93)	7.79 (1.08)	8.37 (1.06)	8.93 (0.71)	11.25 (1.72)
10	0.91 (0.34)	3.19 (0.49)	5.79 (0.65)	8.05 (0.89)	9.97 (0.81)	11.13 (0.96)	12.62 (1.92)	15.41 (3.25)
15	2.20 (0.54)	5.15 (0.49)	9.10 (1.17)	12.04 (1.29)	15.37 (1.64)	19.93 (3.31)	20.45 (2.66)	22.94 (2.25)
20	3.18 (0.52)	7.19 (1.35)	13.20 (3.67)	14.36 (3.07)	16.84 (1.73)	18.26 (2.70)	21.23 (4.67)	26.38 (4.73)
25	3.28 (0.48)	9.46 (0.94)	15.32 (3.08)	16.90 (2.16)	20.07 (2.20)	24.06 (3.54)	28.17 (3.97)	30.89 (5.89)
30	4.67 (0.62)	12.77 (2.64)	16.76 (2.24)	18.38 (2.26)	23.83 (4.57)	26.19 (5.02)	25.85 (5.04)	27.53 (6.49)
35	6.52 (1.11)	19.60 (8.40)	21.25 (4.64)	23.77 (5.35)	30.82 (11.25)	30.84 (8.17)	34.81 (8.68)	41.38 (13.90)
40	8.17 (0.95)	14.00 (1.34)	20.22 (1.83)	23.23 (2.80)	25.59 (4.28)	26.39 (1.61)	26.95 (1.68)	28.54 (5.37)

Table A7. Mean oven-dry wood mass loss (ML_{wood}) and (standard deviation) of 10 European beech (*Fagus sylvatica* L.) wood specimens removed in 2-week intervals over 16 weeks of incubation under soil conditions with water-holding capacity (WHC_{soil}) of 60%, soil moisture content (MC_{soil}) of 60%WHC_{soil}, and alternating soil temperature ($Temp_{soil}$).

Temp. [°C]	Exposure Interval [Weeks]							
	2	**4**	**6**	**8**	**10**	**12**	**14**	**16**
10/20	1.92 (0.35)	4.61 (0.39)	8.02 (1.2)	9.97 (0.6)	12.24 (1.31)	13.37 (1.52)	14.86 (2.13)	19.15 (6.64)
10/30	2.5 (0.51)	5.91 (0.53)	9.48 (1.65)	11.7 (2.29)	14.68 (4.5)	18.8 (4.14)	18.74 (2.67)	21.56 (4.72)
20/30	4.16 (0.51)	7.52 (0.99)	12.24 (2.62)	14.43 (2.23)	16.78 (2.58)	18.03 (1.57)	24.43 (4.46)	27.48 (7.78)

Table A8. Mean oven-dry wood mass loss (ML_{wood}) and (standard deviation) of 10 European beech (*Fagus sylvatica* L.) wood specimens removed in 2-week intervals over 16 weeks of incubation under soil conditions with water-holding capacity (WHC_{soil}) of 60%, soil moisture content (MC_{soil}) of 90%WHC_{soil}, and constant soil temperature ($Temp_{soil}$).

Temp. [°C]	Exposure Interval [Weeks]							
	2	**4**	**6**	**8**	**10**	**12**	**14**	**16**
5	0.32 (0.37)	0.62 (0.32)	0.81 (0.41)	1.13 (0.55)	1.46 (0.53)	1.93 (0.60)	1.66 (0.77)	1.81 (0.27)
10	0.89 (0.44)	2.24 (0.29)	3.16 (0.61)	4.53 (0.49)	5.79 (0.73)	6.43 (0.68)	7.07 (1.80)	7.42 (0.95)
15	0.87 (0.57)	1.90 (0.42)	1.02 (0.54)	1.14 (0.25)	1.73 (0.36)	2.09 (0.43)	2.87 (0.78)	3.04 (1.33)
20	1.56 (0.36)	2.52 (0.43)	3.75 (0.60)	4.60 (0.85)	5.70 (1.13)	7.03 (1.69)	8.73 (1.48)	8.70 (1.02)
25	3.60 (0.78)	6.75 (2.13)	8.09 (1.59)	7.80 (1.80)	10.85 (2.08)	11.72 (3.09)	13.73 (3.19)	15.97 (1.76)
30	3.05 (0.45)	4.13 (0.59)	5.06 (0.76)	6.08 (0.70)	7.03 (1.33)	8.47 (1.69)	9.95 (1.61)	12.03 (2.14)
35	2.08 (0.41)	2.91 (1.10)	3.34 (0.55)	5.09 (1.19)	5.87 (1.05)	6.40 (1.12)	6.97 (1.86)	8.29 (2.37)
40	6.04 (0.63)	10.76 (1.92)	12.53 (1.86)	12.98 (3.00)	13.74 (2.42)	13.47 (1.74)	13.09 (2.68)	14.94 (3.61)

Table A9. Mean oven-dry wood mass loss (ML_{wood}) and (standard deviation) of 10 European beech (*Fagus sylvatica* L.) wood specimens removed in 2-week intervals over 16 weeks of incubation under soil conditions with water-holding capacity (WHC_{soil}) of 60%, soil moisture content (MC_{soil}) of 90%WHC_{soil}, and alternating soil temperature ($Temp_{soil}$).

Temp. [°C]	Exposure Interval [Weeks]							
	2	**4**	**6**	**8**	**10**	**12**	**14**	**16**
10/20	1.27 (0.3)	2.64 (0.54)	3.72 (0.69)	4.67 (1.09)	6.42 (1.45)	7.67 (1.18)	9.61 (2.11)	8.9 (1.78)
10/30	1.23 (0.45)	1.81 (0.67)	2.27 (0.36)	3.12 (0.49)	3.8 (0.56)	4.8 (0.91)	4.39 (1.27)	5.14 (1.37)
20/30	1.00 (0.49)	1.46 (0.57)	1.93 (0.65)	3.04 (3.43)	3.06 (0.7)	4.63 (1.96)	4.54 (1.69)	5.06 (1.68)

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