Biodeterioration Models for Building Materials: Critical Review

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Abstract: Biodeterioration of building materials due to poor hygrothermal conditions is a major concern for the sustainability of buildings and the health and safety of occupants. The risks of biodeterioration are accentuated in high-efficiency buildings, requiring further design considerations. Researchers across the world have tried to characterize this issue through a combination of field experience, modeling, and controlled laboratory investigations. However, integration of these research outputs in building enclosure design analysis is an unfinished agenda, partly due to the lack of coordination between engineering researchers, building enclosure designers, and biologists. This paper critically reviews the research to date on biodeterioration models of building materials (e.g., wood) from the perspective of a building scientist and identifies the needs for further research initiatives that will facilitate the integration of biodeterioration models in building enclosure design analysis through national and international building code regulations and standards. **DOI: 10.1061/(ASCE)AE.1943-5568.0000366.** *© 2019 American Society of Civil Engineers.*

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Introduction

Buildings pose an incredible burden on the environment, particularly with respect to climate change, from their construction (embodied energy and carbon), continued operation and maintenance, and demolition. Studies suggest that up to 45% of North American CO_2 emissions are created from building operation (EPA 2017), and the Intergovernmental Panel on Climate Change identifies the building sector as one of the most receptive for cost-effective carbon emission reductions (IPCC 2014). Energy-efficiency measures, including the efficient use of material, can drastically reduce the environmental impact of buildings, leading to innovative materials and building enclosure assemblies that decrease building energy loads. However, the coupling of decreased heat flow with inadequate moisture management has led to severe premature damage of exterior building enclosures due to biodeterioration of building materials. Inadequate moisture management can also result in poor indoor air quality and occupant health issues. Methods are therefore required to evaluate the potential impact of moisture on the durability and serviceability of building elements.

The challenge of characterizing biodeterioration, defined as biological activities that impair building function (e.g., mold, rot, stains), has been attempted by many North American and European building practitioners and researchers. A diverse range of experts from varied fields, such as biologists, food scientists, physicists, architects, and engineers, have tried to broach the subject from different angles, leading to vast conceptual variations and occasional contradictions, causing shortcomings in model predictive capacities and utility. A multidisciplinary approach, with expertise in design and construction, mycology (the study of fungi), statistical modeling, hygrothermics, and wood sciences, is required to adequately address the complexity of biodeterioration in buildings.

This systematic review identifies and critically analyzes some of the leading deterioration models, with the intent to provide a list of models and their best suited applications. As part of this analysis, the underlying experimental protocols are critiqued, which provides insight into the operating mechanisms, limitations, and strengths of the models. Finally, based on the observed common limitations of the deterioration models, recommendations are made for future investigation. Predicted durability guidelines (MacKenzie et al. 2007) and fungal growth tables (Morris et al. 2007) are beyond the scope of this paper.

Background

Building enclosure durability is a complex interplay of heat, air, and moisture flows combined with biological and chemical variables, such as type of biological agent, substrate nutrient density, alkalinity, and presence or absence of biological antagonists. Heat, air, and moisture response, while well defined under idealized or static conditions, become similarly challenging under dynamic conditions. To assist in characterizing the hygrothermal behavior (heat, air, and moisture), multiple transient computer-based simulation tools have been developed (DELPHIN; hygIRC; WUFI).

Transient hygrothermal simulation tools are used in two main functions: first, to create preliminary evaluations of proposed building enclosures; and second, to probe the underlying hygrothermal behavior of existing building enclosures. The main benefit

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offered by biodeterioration or fungal models is as an extension to the hygrothermal simulation results to add a level of quantitative analysis that is otherwise left to subjective evaluation of the practitioner. Some of the extrapolations of the biodeterioration models include guidance for building codes to reduce durability risks.

The hourly hygrothermal outputs vary depending on the simulation tool, but typically include a moisture metric (e.g., relative humidity, moisture content, water content) and temperature. These serve as inputs to the biodeterioration model, usually with a set of assumptions. For many applications, fungi are used as the predominant indicator organism for deterioration, although bacterial, insectoid, and animal organisms may also affect durability.

The fungi domain is divided by wood scientists into two broad categories based on the impact on the substrate: (1) surface molds, and (2) wood-rotting basidiomycetes (WRBs). Surface molds pose little structural risk to the substrate, whereas WRBs may create life-safety hazards from structural decay. This is contrasted by mycologists, who categorize fungi phylogenetically, with the two broad phyla of interest consisting of ascomycetes (e.g., molds) or basidiomycetes (e.g., decay agents), although both phyla can behave both as surface molds and decay agents. The variation in perspective between these two professions is their respective area of focus: the substrate or the fungi.

Types of decay are further identified by soft rots, brown rots, sequential white rots, and simultaneous white rots, classified mainly by the metabolic residues and digestive pathways. However, this falls beyond the scope of this review and has been addressed by a number of researchers (Schmidt 2006; Zabel and Morrell 1992). The health impacts of mold are similarly well documented in multiple medical papers, journals, and regulations (World Health Organization 2009; Institute of Medicine 2004; Burge 2001; Uzunovic et al. 2011, 2003). It is sufficient to state that those with impaired immune systems are at high risk of mycoses, those with allergic responses may also experience negative symptoms, and those working in environments of high fungal spore loads may become sensitized and develop allergenic responses. For healthy individuals, the risks posed by mold appear minimal.

The interest in fungal modeling has led to previous literature reviews (Vereecken and Roels 2012; Gradeci et al. 2017). However, the novel approach contained herein includes both mold and decay and a focus on North American characteristics (wood and fungal species, construction practices), and extends the review to also evaluate the merits of the models based on mathematical and biological mechanisms.

Biodeterioration Models

Models are mathematical representations of reality, quantifying the relationship between explanatory variables to a response variable. Biodeterioration models typically incorporate environmental and material data and produce a durability risk score. Temperature, moisture [relative humidity (RH), moisture content (MC), water activity (a_w), and water potential (φ)], and substrate properties (e.g., alkalinity, nutrient density, hygroscopicity) are some of the known variables for fungal growth. However, the relationships between these parameters to fungal growth are derived by various means and implemented in different ways. The method used in this paper to evaluate the models is based on the adequacy of the model structure (e.g., mathematical representation), selection of parameters, biological and mycological merits (including experimental protocols), and ease of use. Summary tables of the models and their salient properties are provided in Tables 1–3.

Model Structures

Several model structures have been proposed, such as dose–response models (Altshuler 1981; Pliska 1987; Brischke and Rapp 2008; Isaksson et al. 2010), growth models (Sedlbauer et al. 2003; Ayerst 1969; Smith and Hill 1982), and regression models (Viitanen and Bjurman 1995), to relate biodeterioration to the explanatory variables (e.g., substrate type, temperature, water activity). These relationships may be causal, where a mechanism of action can be established, or correlative, where the interdependence is described

Table 1. Summary of index fungal models

Name	Source	Fungi	Moisture	Substrate	Germination or growth	Recession	Experimental source
RHT80 index	Mukhopadhyaya et al. (2009)	Mold	RH	N/A	No	No	N/A
RHT95 index	Wang and Morris (2011)	*Gloeophyllum trabeum*, *Trametes versicolor*	RH	Plywood, oriented strand board (OSB), solid Wood	No	No	Original
Mold index	Johansson et al. (2010)	*Cladosporium* spp.	RH	Rendered façade	Germination	Yes	Multiple, including: Grant et al. (1989)
Limit-state dose–response	Isaksson et al. (2010)	*Aspergillus versicolor*, *Cladosporium sphaerospermum*, *Penicillium* spp., *Aureobasidium pullulans*	RH	*Pinus*, *Picea*	Germination	Yes	Viitanen (1997)
Mold-resistant design	Thelandersson and Isaksson (2013)	*Eurotium herbariorum*, *Aspergillus versicolor*, *Penicillium chrysogenum*, *Aureobasidium pullulans*, *Cladosporium sphaerospermum*, *Stachybotrys chartarum*	RH	*Pinus*, *Picea*	Germination	Yes	Viitanen (1997)
Dose–response	Brischke and Rapp (2008)	Decay	MC	*Pinus sylvestris*, *Pseudotsuga menziesii*	Germination	No	Original

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Table 2. Summary of threshold fungal models

Name	Source	Fungi	Moisture	Substrate	Germination or growth	Recession	Experimental source
Temperature ratio	Hens (1991)	*Aspergillus versicolor*	N/A	Agar	No	No	N/A
RH threshold	Hens (1999)	*Aspergillus versicolor*	RH	Agar	No	No	N/A
ASHRAE 160	ASHRAE (2009)	*Aspergillus versicolor*	RH	Agar	No	No	N/A
Isopleth	Ayerst (1969), Smith and Hill (1982)	*Aspergillus restrictus, Aspergillus versicolor*	RH	Agar	No	No	Original
ESP-r	Clarke et al. (1999)	*Aspergillus niger*, *Aspergillus versicolor*, *Penicillium chrysogenum*, *Cladosporium sphaerospermum*, *Ulocladium consortiale*, *Stachybotrys chartarum*	RH	Agar	No	No	Clarke et al. (1996)
Clarke et al (1996) Biohygrothermal	Sedlbauer (2001), Sedlbauer et al. (2003)	Lowest isopleth for mold (LIM)	RH	Types 0, I, and II	Yes	No	Smith and Hill (1982), Ayerst (1969)
Mold germination	Moon (2005)	LIM	RH	Types 0, I, and II	Yes	No	Sedlbauer (2001)

Table 3. Summary of empirical fungal models

Name	Source	Fungi	Moisture	Substrate	Germination or growth	Recession	Experimental source
VTT	Viitanen (1997), Viitanen and Ojanen (2007), Ojanen et al. (2010), Viitanen et al. (2010b)	*Aspergillus versicolor*, *Cladosporium sphaerospermum*, *Penicillium* spp., *Aureobasidium pullulans*	RH	*Pinus sylvestris*, *Picea abies*, others	Yes	Yes	Original
VTT fungal decay	Viitanen et al. (2010a)	*Coniophora puteana*, *Gloeophyllum sepiarium*	RH	*Pinus sylvestris*, *Picea abies*	Germination	Yes	Viitanen (1997)
IRC	Nofal and Kumaran (2011)	*Coniophora puteana*, *Gloeophyllum sepiarium*	RH	*Pinus sylvestris*, *Picea abies*	Germination	Yes	Viitanen (1997)
Wood degradation model	Saito et al. (2008, 2012), Saito (2017)	*Fomitopsis palustris*	RH	*Pinus densiflora*	Growth	No	Original

mathematically. Generally, correlative relationships are less robust than causal relationships because the validity only applies under the set of circumstances by which the relationship was derived. Models are further categorized as deterministic or stochastic. Deterministic models are fully explained by the defining parameters and initial conditions and provide unique solutions, whereas stochastic models are based on probability distributions of the defining parameters resulting in nonunique outputs.

Selection of Parameters

Multiple parameters may be used to fit the explanatory variables to the response variables. These include environmental data (e.g., temperature, moisture), biological data (fungal types, biological inhibitors, internal competition), and substrate impacts (substrate type, substrate nutrient density, substrate hygroscopicity). The selection of these parameters for the individual models is scrutinized based on their known impact on fungal growth.

Biological and Mycological Merits

A fungal model based on mycological principles is a requirement for accuracy and robustness. An understanding of the condition required for fungal metabolic activities and of the reproductive life cycles helps clarify what the model is attempting to quantify. Inadequate consideration of biological parameters may generate models that are not representative of known fungal behavior. While the results of the model may nonetheless be accurate, these may be a result of overfitted parameters and may lose their accuracy at the extremes of the fitted value ranges.

Classification of Biodeterioration Models

The fungal models reviewed generally fall into three categories, roughly ascribed by the method of reasoning: deductive, inductive, and abductive. For simplicity, they are described functionally, as indexes that correlate a degree of fungal growth with an index based on empirical observations (e.g., it ascribes a score to the X environmental conditions, which is then correlated to a Y fungal metric); thresholds that define the limiting conditions required for growth and infer extent of growth based on environmental conditions (e.g., with X environmental conditions that surpass the known limiting conditions, we anticipate a Y fungal metric); and empirical, which is not to say that empirical elements are not included in the other elements, but rather that the response variable is regressed to the explanatory parameters to describe the expected extent of fungal growth (e.g., X environmental conditions are known to correlate with a Y fungal metric).

Indexes

Index models quantify environmental parameters and correlate the product with an extent of deterioration. The link function between

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the product of the explanatory variable may be regressed with empirical data. Mathematically, index models are categorically defined in Eq. (1)

$$\text{Fungal Growth} \propto g^{-1}(f(P_1, P_2, \ldots, P_n)) \tag{1}$$

where P_1 to P_n = explanatory parameters; f = linear predictor; and g = link function that relates the linear predictors to the extent of decay. The relative humidity and temperature (RHT) indexes, mold indexes, and dose–response models are examples of such models where the explanatory variables describe the relationship of the product with fungal growth but do not directly predict extent of fungal growth.

RHT80 and RHT95 Indexes

The RHT index was conceived as part of the Moisture Management for Exterior Wall Systems (MEWS) project, which was tasked with identifying long-term moisture response indicators for risk of deterioration (Mukhopadhyaya 2003); it has also been adopted as part of the International Research Group on Wood Protection (Wang and Morris 2011). The index is a cumulative hourly sum of the moment about a minimum temperature and relative humidity threshold. To minimize corrosion and mold growth, a relative humidity threshold of 80% has been proposed; for decay, the proposed threshold is 95% RH, and a temperature baseline of 5°C is proposed. The relationship is shown in Eq. (2)

$$\text{RHT}_{x,y} = \sum(\text{RH} - \text{RH}_x) \cdot (T - T_y) \mid \text{RH} > \text{RH}_x, \text{ and } T > T_y \tag{2}$$

The model appears to be well correlated to decay risks at near-saturated conditions (Wang and Morris 2011).

Structure

The model is deterministic and dynamic. It uses the RHT base value (80 for corrosion or molds, 95 for decay) as an indicator for risk of deterioration. Temperature and RH are weighted equally and linearly.

Biology

The RHT index is used only as an indicator for risk of growth and does not predict initiation or extent of growth. There are no considerations for substrates, fungal species, or dynamic effects. There are no upper limits to temperature, which may pose concerns for applications where temperatures may exceed 40°C (Johansson et al. 2010). The model does provide capacity for desiccating events, which may reduce the risks of fungal growth.

Applicability

The model is relatively easy to use and transparent in application because it provides a useful metric to compare different cases. However, further validation is required to provide predictive capacities at acceptable levels of performance.

Mold Indexes

The mold index (Johansson et al. 2010) was developed to assess the potential for mold growth of rendered façades over insulation. The basis for the mold was surface temperature and humidity monitoring over a 20-month period on a single test house with different constructions, colors, and orientations. The results are three indexes with increasing layers of variables. The indexes are the time integration of mold growth potential functions for surface temperature, surface relative humidity, and a recovery function to simulate delays in growth after adverse environmental conditions. The most comprehensive of which is described in Eq. (3)

$$I_3 = \int_{t=t_0}^{t_i} f_r(\tau) f_T(\tau) f_\varphi(\tau) \partial\tau \tag{3}$$

where f_T = temperature score curve; f_φ = RH score curve, both shown graphically in Fig. 1; and f_r = recovery factor, and is equal to 0 if the previous time step did not result in any growth (i.e., $I_3 \leq 0$), and otherwise has a value of 1. The combined temperature

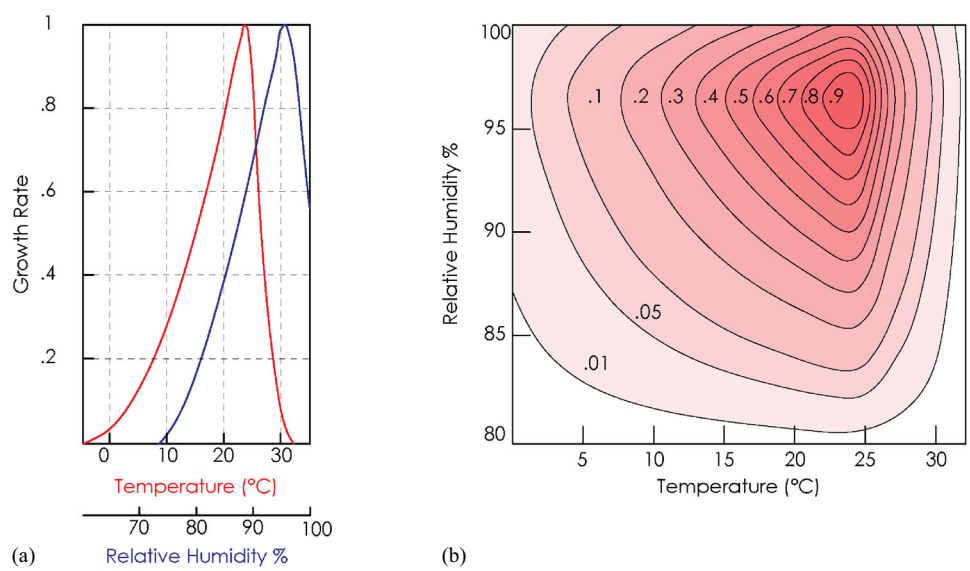

Fig. 1. (a) RH and temperature weighting factors for *Cladosporium* spp. with RH (dark) and temperature (light); and (b) combined RH and T scores. [Adapted from *Building and Environment*, Vol. 45 (5), S. Johansson, L. Wadsö, and K. Sandin, "Estimation of mould growth levels on rendered façades based on surface relative humidity and surface temperature measurements," pp. 1153–1160, © 2010, with permission from Elsevier.]

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and relative humidity scores closely resemble the isopleth plots discussed subsequently.

Structure

The model is deterministic and dynamic. The integration of temperature and relative humidity functions generates a mold potential. However, relative humidity and temperature are confounded, and may have interdependent functions that may not be fully captured in this study. The model indicates only risk of growth and does not provide predictions on start to germination time or extent of growth or recession.

Biology

The fungal species were *Cladosporium* spp. on an unknown substrate because no isopleth data were available to construct species-specific temperature and humidity functions. The fitted temperature and humidity function curves are based on a single study in a single climate and may vary depending on species and substrates.

Applicability

Conceptually, these models are easy to incorporate within a model; however, the temperature and relative humidity equations have not been provided within the paper, aside from graphical format, which renders adoption challenging for practitioners.

Dose–Response for Mold

A dose–response relationship was proposed to describe the magnitude of the response to a given stressor (Isaksson et al. 2010). In fungal models, the stressor (dose) is a period of conditions suitable for fungal growth; the response is a degree of fungal growth. The cumulative dose is described by the product of a temperature and humidity function, described in Eqs. (4)–(6)

$$D = D_\varphi(\varphi_i) \cdot D_T(T_i) \tag{4}$$

$$D_\varphi = \begin{cases} \exp\left[15.53 \cdot \ln\left(\frac{\varphi}{90}\right)\right] \rightarrow 75\% < \varphi \leq 100\% \\ (-2.7 + 1.1 \cdot \varphi/30) \rightarrow 60\% < \varphi < 75\% \\ -0.5 \rightarrow \varphi < 60\% \end{cases} \tag{5}$$

$$D_T = \begin{cases} \exp\left[0.74 \cdot \ln\left(\frac{T}{20}\right)\right] \rightarrow 0.1°\text{C} < T \leq 30°\text{C} \\ -0.5 \rightarrow T < 0.1°\text{C} \end{cases} \tag{6}$$

where D_φ = dose generated by daily average relative humidity φ_i; and D_T = dose created by the daily average temperature T_i. The term D is expressed in number of days and N_{ref} is the reference number of days for a specific climate resulting in mold growth. Mold onset is anticipated when the ratio of D to N_{ref} is equal to 1. Eqs. (5) and (6) describe the dose for relative humidity and temperature.

Structure

The model is deterministic and dynamic, with separation of the temperature and humidity variables combined to create an aggregate dose of fungal growth. This model predicts time until growth, but not extent or severity.

Biology

The concern with dose–response models is the response may vary nonlinearly with time and other conditions (e.g., rate of fungal growth is not linear). It is uncertain whether such models are applicable for the growth of living organisms. The calibration data set was provided by Viitanen and Ritschkoff (1991) and was based on fungal growth on pine and spruce. Critically, this model considers fungal recession under inclement conditions. Despite a statement of following a limit-state concept, the resistance factors for the substrate were not included.

Applicability

This model builds on other indexes with additional layers of complexity but is nonetheless easily applicable for practitioners. As with other indexes, the product of a temperature and RH function provides straightforward and transparent results.

Mold Resistance Design Model

The mold resistance design (MRD) model (Thelandersson and Isaksson 2013) builds on previous work by Isaksson et al. (2010), but with a more generalized form and with a new data set. Increased accuracy is provided by further subdividing the dose into 12-h intervals. The framework of this model is based on a dose–response relationship to determine time of germination

$$D_{12} = D_\varphi(\varphi_{i,12}) \cdot D_T(T_{i,12}) \tag{7}$$

$$D_\varphi = \begin{cases} 0.5 \cdot \exp\left[15.5 \cdot \ln\left(\frac{\varphi_{12}}{90}\right)\right] \rightarrow 75\% < \varphi_{12} \leq 100\% \\ (-2.118 + 0.0286 \cdot \varphi_{12}) \rightarrow 60\% < \varphi_{12} < 75\% \\ -0.4 \rightarrow \varphi_{12} < 60\% \end{cases} \tag{8}$$

$$D_T = \begin{cases} \exp\left[2.0 \cdot \ln\left(\frac{T_{12}}{20}\right)\right] \rightarrow 0.1°\text{C} < T \leq 30°\text{C} \\ -0.4 \rightarrow T < 0.1°\text{C} \end{cases} \tag{9}$$

where D_φ = dose generated by 12-h average relative humidity φ_i; and D_T = dose created by the 12-h average temperature T_i. The term D is expressed in number of days and N_{ref} is the reference number of days for a specific climate resulting in mold growth. Mold onset is anticipated when the ratio of D to D_{crit}, the point of fungal germination at 90% RH and 22°C, reaches a value of 1.

Structure

The model is deterministic and dynamic. Only five different test conditions were assessed; the lowest and highest temperatures were 10°C and 22°C, respectively, which therefore necessitates extrapolation for temperatures falling beyond these ranges, leading to concerns of uncertainty. Once the equivalent dose is determined, it is normalized to a baseline growth (22°C and 90% RH). Negative doses are used to try to reconcile suboptimal environmental conditions. The MRD is only able to predict onset of mold, not projected extent.

Biology

Multispecies suspensions of common buildings molds are used in the model and it incorporates data with a different set of fungi. Normalizing the dose to a relative control helps resolve the nonlinearity issue of dose–response models in describing biological growth, but nonetheless does not describe the actual extent of fungal growth, only the description of the equivalent dose.

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Applicability

The model is readily integrated with hourly output from hygrothermal simulation models. Validation with experimental evidence suggests further refinement is required to improve accuracy and reliability.

Dose–Response for Decay

The dose–response relationship (Brischke and Rapp 2008) was used to establish the extent of decay from wood-rotting basidiomycetes on 27 test sets in 23 different field exposure conditions across Europe over a period of 7 years. The samples consisted of prisms of Scots pine (*Pinus sylvestris* L.) and Douglas fir heartwood (*Pseudotsuga menziesii* Franco) stacked in accordance with European standard EN 335-2006 (CEN 2006). The prisms were scored on the mean decay rating from EN 252-1986 (CEN 1986). The doses as a function of moisture content and temperature are shown in Fig. 2, derived from Eqs. (10)–(12)

$$d_{\text{daily}} = d_{\text{MC}} \cdot d_T \tag{10}$$

$$d_{\text{MC}} = 6.75 \times 10^{-10}\text{MC}^5 - 3.50 \times 10^{-7}\text{MC}^4 + 7.18 \times 10^{-5}\text{MC}^3 - 7.22 \times 10^{-3}\text{MC}^2 + 0.34 \times \text{MC} - 4.98 \tag{11}$$

$$d_T = -1.8 \times 10^{-6}T^4 + 9.57 \times 10^{-5}T^3 + 1.55 \times 10^{-3}T^2 + 4.17 \times 10^{-2}T \quad \text{for all } -1°\text{C} \leq T \leq 40°\text{C} \tag{12}$$

where d_{MC} = dose generated by daily average moisture content MC; and d_T = dose created by the daily average temperature T.

Structure

The model is deterministic and dynamic and uses temperature and moisture content to describe the extent of decay, not fungal growth. The moisture contents for the wood samples were calibrated, but obtaining the moisture content variables to input into the model can be challenging, as the accuracy of electrical resistance–based moisture content readings are unreliable beyond the fiber saturation point (Forest Products Laboratory 2010; Skaar 1988; Siau and Avramidis 1996).

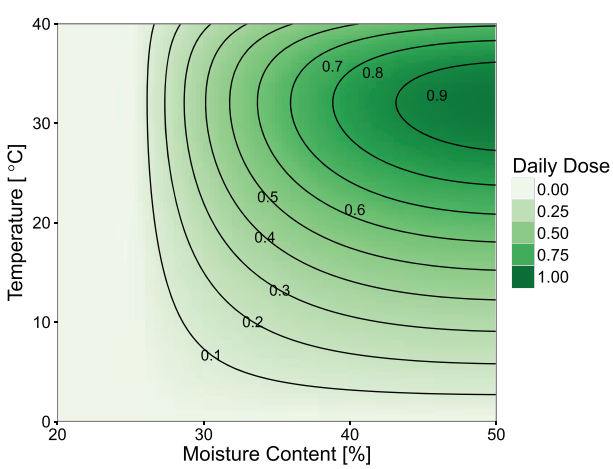

Fig. 2. Daily temperature and moisture content dose values for decay. (Data from Brischke and Rapp 2008.)

Biology

The field exposure tests provide a broad range of natural fungal inoculation, which causes difficulty in assessing effects of fungal spore loads based on the different locations and even between samples. The applicability of the stacked prism method does not provide realistic test conditions for all building assemblies.

Applicability

This model is best applied for scenarios involving decay and exposure to liquid water. It benefits from using a pick-test, which assesses structural features of the wood, instead of other observational metrics. Recommendations on acceptable dose level are not provided, although a mean decay rating of less than 1 can be achieved from dose ranges of 200–475 units.

Thresholds

Threshold models define the limiting boundary conditions for fungal growth under which a change in the response variable is anticipated. Isopleth models, which characterize the limiting conditions of temperature and relative humidity, are one such example; strict threshold limits for fungal growth under certain environmental parameters are another (i.e., not to exceed 80% RH over a duration of 30 days). The biohygrothermal model, while slightly different than other isopleth or threshold models, nonetheless uses the observed environmental conditions relative to the limiting growth conditions to infer the extent of contamination. Threshold models are mathematically represented in Eq. (13)

$$\text{Fungal Growth} \geq \begin{cases} D_1 = f_1(P_1, P_2, \ldots, P_n) \mid \text{Condition 1} \\ \vdots \\ D_n = f_n(P_1, P_2, \ldots, P_n) \mid \text{Condition } n \end{cases} \tag{13}$$

where P_1 to P_n = explanatory parameters used to define the decay functions, f_n (which may be a binary pass or fail) under a set of conditions.

Isopleths

Ayerst (1969) provides one of the pioneering relationships between relative humidity and temperature for two fungal species on malt agar strips. The malt agar strips were placed in temperature-controlled chambers; humidity was controlled with salt solutions. A total of 30 isolates of 12 species of *Apergillus* spp., *Penicillium* spp., and *Stachybotrys chartarum* were tested over a range of water activity and temperatures. Smith and Hill (1982) replicated the study on *Aspergillus versicolor* and *Aspergillus restrictus* with relatively similar results, shown in Fig. 3.

Structure

The structure is steady state and deterministic. These isopleths provide the germination times and mycelial growth rates for a range of temperature and water activity conditions. The steady-state nature of these experiments is unable to predict time until germination or extent of growth in dynamic environmental conditions. The effects of unfavorable conditions are not included.

Biology

The study focused on *Aspergillus restrictus* and *Aspergillus versicolor* on malt agar in constant temperature and RH conditions; they may yield significantly different results on different substrates.

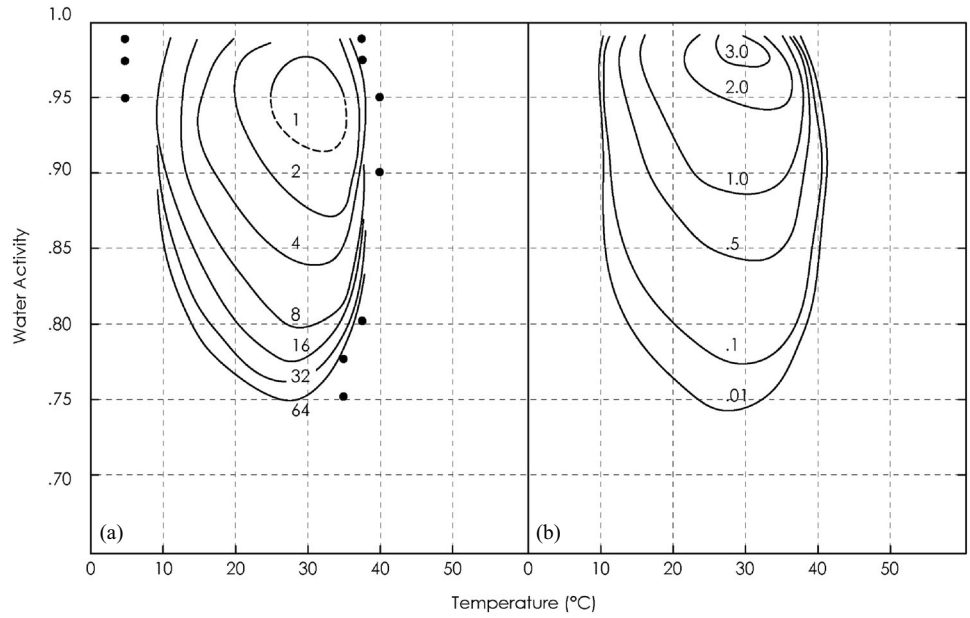

Fig. 3. (a) Germination time (days); and (b) growth rate (mm/day) for *Aspergillus versicolor*. Black dots indicate conditions under which germination had not occurred after 95 days. [Reprinted from *Transactions of the British Mycological Society*, Vol. 79 (3), S. L. Smith and S. T. Hill, "Influence of temperature and water activity on germination and growth of *Aspergillus restrictus* and *A. versicolor*," pp. 558–560, © 1982, with permission from Elsevier.]

Applicability

Simplicity lends itself to use as a guideline. However, these models are unable to include exposure times and are thus unable to adequately predict fungal growth as a function of dynamic temperature and moisture conditions.

Temperature Ratio, RH Threshold, and ASHRAE 160 Criteria for Moisture-Control Design Analysis in Buildings

These three threshold models are all incremental developments from the original International Energy Agency (IEA) Annex 14 final reports (IEA 1991). The temperature ratio model (Hens 1991) was designed to implement a practical approach to minimize condensation and mold risk; the RH threshold (Hens 1999) further refines the limiting RH conditions for fungal growth; and the ASHRAE 160 (ASHRAE 2009) standard provides explanatory material for assessing and modeling fungal growth risk.

Mold germination was assumed to be determined strictly on the fungi's minimum germination threshold as a function of the surface saturated vapor pressure. IEA Annex 14 (IEA 1991) forms one of the first pioneering works for establishing a minimum threshold for fungi as applied to the built environment. The ratios were devised from a heat and moisture balance on the surface of interior plaster. Mold germination was related to Eq. (14), whereas the minimum surface temperature to avoid mold growth is found in Eq. (15)

$$p \geq a \cdot p'_{si} \tag{14}$$

$$\tau = \frac{\theta_{s,\min} - \theta_e}{\theta_i - \theta_e} \geq 0.7 \tag{15}$$

where p = surface vapor pressure; p'_{si} = saturated surface vapor pressures; a = fungal coefficient representing the minimum surface relative humidity to support mold germination; θ_i and θ_e = interior and exterior air temperatures; and $\theta_{s,\min}$ = minimum surface temperature.

The RH threshold builds on the definition of a in the original IEA Annex 14 work by determining the lowest relative humidity as a function of temperature (Hens 1999). The threshold relationship is shown in Eq. (16)

$$\varphi_{\text{threshold}} = 0.033\theta^2 - 1.5\theta + 96 \tag{16}$$

IEA Annex 14 demonstrated that higher relative humidity conditions are required at shorter durations to stimulate fungal growth, and consequently Hens (1999) provided an updated logarithmic curve describing this relationship [Eq. (17)]

$$\varphi_{wT} = \min\left[1, 0.8 \cdot (1.25 - 0.0588\ln(t))\right] \tag{17}$$

The ASHRAE 160 standard builds on the original IEA Annex 14 work by providing methods and protocols to specify performance-based design criteria for predicting moisture-related damage risks to the building. It is divided into three sections: (1) criteria for selecting analytic procedures, (2) criteria for input, and (3) criteria for evaluation. The conditions necessary for minimizing mold growth are a 30-day running average surface RH less than 80%, a 7-day running average surface RH less than 89%, and a 24-h running average surface RH less than 100%. ASHRAE 160–2009 had a transcription error listing the 7-day average RH as 98% instead of 89%. It also goes beyond the IEA Annex by also stipulating minimum and maximum temperatures, 5°C and 40°C, respectively.

Structure

These models only consider temperature as the input variable, and then provide the limiting RH conditions. These models do not provide risk of fungal growth nor anticipated duration until germination, but instead only provide a conservative threshold for avoiding mold growth.

Biology

Dynamic influences were discussed, but not included in the assessment. The assumed temperatures ranged only from 20°C to 25°C

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for the temperature index. The a coefficient was intended to aggregate multiple fungal growth properties (e.g., species, nutrients, substrate), but the limiting values were established based on *Aspergillus versicolor* on an agar substrate, which was observed to not grow at water activity (a_w) levels below 0.75, with growth on building materials infrequent for RH below 85%. A compromise at $0.8a_w$, the water activity or equilibrium RH of a material with its surroundings, appears to have been agreed upon by the IEA committee to provide a degree of safety. This results in an a value to use as a coefficient for a factor of safety, as opposed to a descriptor of anticipated growth. To account for time-scale influences, the minimum RH thresholds were modified to 100, 89, and 80% for 1 day, 1 week, and 1 month, respectively.

Applicability

Simplicity lends itself to use as a guideline. However, these models are unable to predict fungal growth. The ASHRAE 160 (ASHRAE 2016) standard has since been updated to adopt the underlying foundation of the VTT Technical Research Centre of Finland (VTT) mold growth model (Viitanen et al. 2010b).

ESP-r Model

ESP-r (Clarke et al. 1999) is a building energy simulation model with an ability for higher temperature resolutions at designated areas. This can provide time-series surface temperatures at areas of concern, such as thermal bridges. With surface temperatures and modeled interior humidity conditions, evaluations based on mold growth risks are enabled. The internal fungal database is divided into six categories based on the minimum level of relative humidity required for germination. Plotting the weekly average condition onto the isopleth plot is then used to infer the risk and type of fungi.

Structure

With the isopleth data derived from steady-state conditions, dynamic effects cannot be considered. The model is unable to predict time until germination, but rather risk of growth and type of anticipated fungal classes.

Biology

A cross-sectional study on fungi in Scottish homes was used to develop and categorize the types of fungi (Clarke et al. 1996). It was stated that most of the fungi were from the Deuteromycota subgroup, but many of the represented fungi were from the Ascomycota phylum. It is also unknown under what conditions the isopleths were derived.

Applicability

Because this is an extension to the ESP-r program with little guidance on use, this model does not lend itself to widespread use. The minimum duration above the isopleth is also not explicitly stated, rendering application of this model challenging.

Biohygrothermal Model

The biohygrothermal model (Sedlbauer 2001; Sedlbauer et al. 2001, 2003) is an extension module for the hygrothermal software WUFI. It is an improvement on the Fraunhöfer lowest isopleth for mold (LIM) approach (Sedlbauer et al. 2001). The approach combines isopleth limits with a heat and moisture balance on a theoretical fungal spore. Germination is defined as the point at which the internal moisture content and temperature of the spore fall within an accepted range, which is dependent on the type of substrate. Sedlbauer (2001) suggests ranges between 20% and 25% by volume based on the substrate LIM.

Table 4. Category classes for biohygrothermal model

Substrate category	Description
0	Optimal culture medium
1	Biologically recyclable building materials
2	Biologically adverse recyclable building materials
3	Building materials that are neither degradable nor contain nutrients

Source: Data from Sedlbauer et al. (2003).

The extent of mycelium growth is determined on a modification of the isopleth graphs. Hazard classes are created for different fungi based on the potential pathogenic and allergenic effects in humans, with distinguished LIM curves. Substrates are also considered to a greater extent than they are in other models, with the addition of four substrate classes, shown in Table 4.

Structure

The biohygrothermal model is deterministic and dynamic. A significant advantage is the dynamic heat and moisture flow outputs from the front-end software, which permits greater precision than would otherwise be found in most other mold growth models. Estimates about the extent of growth are based on isopleth plots, which are based on steady-state experiments.

Biology

The theoretical hygrothermal properties of the conidia, such as vapor permeance of the spore wall and minimum moisture content for germination, were estimated from laboratory experiments on *Aspergillus restrictus* under steady-state conditions using laboratory data from Smith and Hill (1982). The LIM curve used for the model is a conservative estimate for a number of different fungal species and is shown in Fig. 4.

The water retention curves for fungi spore were assumed to be similar to bacterial spores (Sedlbauer et al. 2001), which may not be compatible because the cell wall constituents of bacteria and fungi are different, including appreciable differences in life cycles and niches (Schmidt 2006). With the small size of conidia, it was assumed that hygrothermal properties are scalable from 3 μm to 1 cm. However, at these smaller scales, the assumptions of the Kelvin equation only appear to apply at relative humidities above 80% (Skaar 1988; Thygesen et al. 2010); thus, assumptions about water retention curves below this value are uncertain. The lower values of the water retention curve may be explained by the hygroscopicity of the cell wall and osmotic pressures created by the cytoplasm.

Applicability

The biohygrothermal model is readily included as part of the WUFI Pro software, an industry standard hygrothermal simulation tool, and so does not present as great of a challenge for adoption. However, further validation of the biohygrothermal model is required because preliminary results suggest a poor relationship with 1,388 homes in the United Kingdom (Altamirano-Medina et al. 2009).

Mold Germination Graph Method

The mold germination model (Moon 2005) attempts to quantify uncertainty by using stochastic methods to define the risk of growth. Four causal categories are proposed sources of uncertainty: spore availability, substrate condition, mechanical system operation and maintenance, and building detail.

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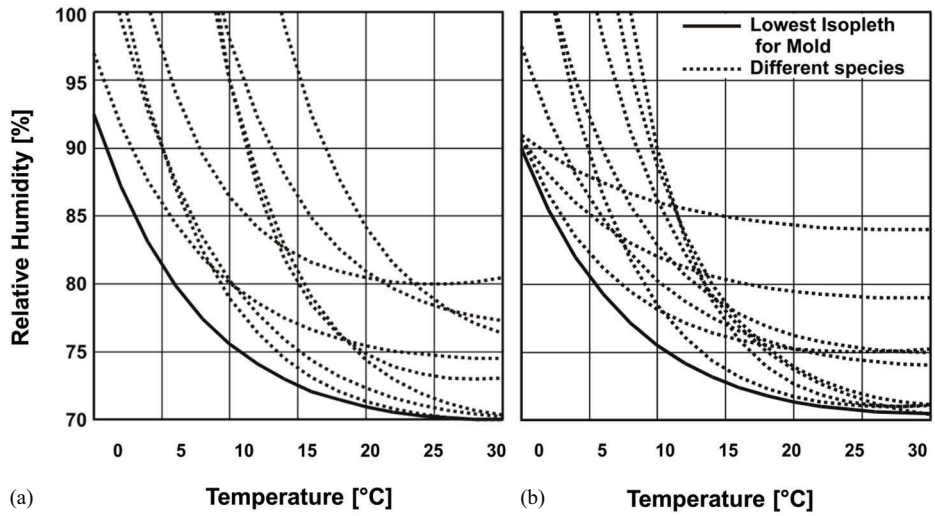

Fig. 4. Lowest isopleths for (a) germination; and (b) mycelial growth. (Reprinted with permission from Sedlbauer 2001.)

Structure

The model uses stochastic inputs and a dynamic approach to isopleth tables by tabulating the number of days in which conditions are sufficient for germination in accordance with the germination isopleths. The number of days for potential growth are tabulated over the year to determine the risk. The model only focuses on germination and does not address the extent of growth.

Biology

It appears that the underlying data were derived from Smith and Hill (1982), and thus the limitations for a single fungal species grown on agar substrates under steady-state conditions apply when considering dynamic environmental conditions.

Applicability

The germination graph method lends itself to ease of use within spreadsheet formats where the hygrothermal data are stored. Insufficient context is provided on whether the output consists of a major or minor risk for mold growth, and thus further guidance is required.

Empirical

Empirical regressions are the deductive result of identifying the impact of explanatory variables directly on the response variable without the use of an intermediary factor. The equations generally predict the extent or occurrence of fungal growth as a direct result of the explanatory parameters. The mathematical relationship is expressed in Eq. (18)

$$\text{Fungal Growth} = f(P_1, P_2, \ldots, P_n) \tag{18}$$

where P_1 to P_n = explanatory parameters used to define the fungal growth functions, f.

VTT Mold Growth Model

The VTT mold growth model (Viitanen 1997; Hukka and Viitanen 1999; Viitanen et al. 2008; Viitanen et al. 2010b) is an empirical model based on controlled laboratory experiments. It has since been adopted by ASHRAE Standard 160 (ASHRAE 2016). The output from the model is the mold index (M), with description provided in Table 5, and is derived from a linear regression on temperature, relative humidity, wood type (spruce and pine), and substrate quality (rough sawn or planed). The model has since undergone several iterations to now include different substrate types. The extent of growth was measured using the mean growth method (Viitanen and Ritschkoff 1991).

Table 5. Mold growth index and description, including new determinations

Index	Description of growth rate
0	No growth
1	Initial stages of growth (microscopic)
2	Coverage <10% (microscopic), several local colonies
3	Fungal coverage <10% (visual), or <50% (microscopic): New spores produced
4	Fungal coverage 10%–50% (visual), >50% (microscopic)
5	Extensive surface coverage, >50% (visual)
6	Heavy and tight growth, ~100% (visual)

Source: Reprinted from Ojanen et al. (2010).

The rate of mold growth is calculated if the relative humidity falls above the minimum RH, governed by Eq. (19)

$$\mathrm{RH}_{\mathrm{crit}} = \begin{cases} -0.00267T^3 + 0.160T^2 - 3.13T + 100; T < 20°\mathrm{C} \\ \mathrm{RH}_{\min}; T \geq 20°\mathrm{C} \end{cases} \tag{19}$$

The mold index is the integration of the rate of mold growth with time, shown in Eq. (20). The time until a mold index of 1 or 3, critical in calculating the k_1 and k_2 coefficients, are provided in Eqs. (21) and (22). In the updated model, values for k_1 and k_2 are provided in Table 3. The time values are given in days, but are in hours in Eq. (26)

$$\left(\frac{dM}{dt}\right) = \left(\frac{k_1 k_2}{7 \cdot t_{M=1}}\right)_{\text{pine}} \tag{20}$$

$$t_{M=1} = \exp\left(-0.68 \cdot \ln(T) - 13.9 \cdot \ln(\mathrm{RH}) + 0.14 \cdot W - 0.33 \cdot SQ + 66.02\right) \tag{21}$$

$$t_{M=3} = \exp\left(-0.74 \cdot \ln(T) - 12.72 \cdot \ln(\mathrm{RH}) + 0.06 \cdot W + 61.5\right) \tag{22}$$

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Table 6. Substrate sensitivity classes with maximum coefficients and descriptions

Sensitivity class	k_1 (max) $M < 1$	k_1 (max) $M \geq 1$	W	k_2 (max) A	B	C	RH_{min}	Notes
Very sensitive	1	2	0	1	7	2	80	Untreated wood, includes lots of nutrients for biological growth
Sensitive	0.578	0.386	1	0.3	6	1	80	Planed wood, paper-coated products, wood-based boards
Medium resistant	0.072	0.097	1	0	5	1.5	85	Cement- or plastic-based materials, mineral fibers
Resistant	0.033	0.014	1	0	3	1	85	Glass and metal products, materials with efficient protective compound treatments

Source: Reprinted from Ojanen et al. (2010).

Table 7. Decline coefficients

C_{mat}	Description
1	Pine in original mode, short periods
0.5	Significant relevant decline
0.25	Relative low decline
0.1	Almost no decline

Source: Reprinted from Ojanen et al. (2010).

The k_1 coefficients represent the time for germination and local growth, and k_2 coefficients correct for asymptotic growth toward the maximum supportable mold growth index at the given environmental conditions. The material corrected values for k_1 and k_2 are shown in Eqs. (23) and (24)

$$k_1 = \begin{cases} \dfrac{t_{M=1,\text{pine}}}{t_{M=1}}, & \text{when } M < 1 \\ \dfrac{2(t_{M=3,\text{pine}} - t_{M=1,\text{pine}})}{(t_{M=3} - t_{M=1})}, & \text{when } M > 1 \end{cases} \tag{23}$$

$$k_2 = \max[1 - \exp(2.3 \cdot (M - M_{\max}), 0] \tag{24}$$

The maximum supportable mold growth $M_{\max}$, based only on RH and substrate type, is shown in Eq. (25)

$$M_{\max} = A + B \cdot \frac{\text{RH}_{\text{crit}} - \text{RH}}{\text{RH}_{\text{crit}} - 100} - C\left(\frac{\text{RH}_{\text{crit}} - \text{RH}}{\text{RH}_{\text{crit}} - 100}\right)^2 \tag{25}$$

The coefficients A, B, and C describe the substrate sensitivity classes, as provided in Table 6.

When the ambient relative humidity falls below the critical threshold, decline may occur. These recessions in the mold index were observed from cyclical testing and vary depending on duration of the inclement period. The rate of decline is governed by Eq. (26)

$$\frac{dM}{dt} = C_{\text{mat}} \cdot \begin{cases} -0.00133, & \text{when } \Delta t \leq 6\,\text{h} \\ 0, & \text{when } 6\,\text{h} < \Delta t \leq 24\,\text{h} \\ -0.000667, & \text{when } \Delta t > 24\,\text{h} \end{cases} \tag{26}$$

The rate of decline was found to vary depending on substrate types, modified by the coefficient C_{mat}, as shown in Table 7.

Structure

The time to reach certain levels of mold growth was regressed to temperature, relative humidity, wood species, and surface quality. It is uncertain if the regressions were verified for normality, heteroscedasticity, and independence of explanatory parameters because any of these can invalidate the regression (Zuur et al. 2010).

The surface water activity was assumed to be equal to the relative humidity in the chamber. During fluctuating humidity conditions, this may not be accurate.

Biology

The cyclical (non-steady-state) conditions lend veracity to the models, but were only conducted over a fairly short duration. The sensitivity classes and C_{mat} coefficient affect rate of growth and decline, respectively, assuming that they are a scalar of the original pine substrate, which may not necessarily hold because there can be significant variations in substrate hygroscopicity and nutrient availability.

Applicability

The model can be adopted in a spreadsheet format with some work. The number of computational steps required renders some challenges in adoption in spreadsheet formats. The determination of the mold recession as a function of the duration of humidity conditions below the limiting threshold can be challenging to those not familiar with programing languages.

VTT Fungal Decay Model

The VTT fungal decay model (Viitanen et al. 2010a) builds on the original doctoral work by Viitanen (1991). The model is divided into two components; the first quantifies the time until onset of decay (α), and the second is a quantification of mass loss as a representation of damage. The time until onset of decay occurs when $\alpha = 1$, described by Eqs. (27) and (28)

$$\alpha(t) = \int_0^t d\alpha = \sum_0^t (\Delta\alpha) \tag{27}$$

$$\Delta\alpha = \begin{cases} \dfrac{\Delta t}{\left(\dfrac{2.3 \cdot T + 0.035 \cdot \text{RH} - 0.024 \cdot T \cdot \text{RH}}{-42.9 + 0.14 \cdot T + 0.45 \cdot \text{RH}}\right)}, & T > 0°\text{C RH} > 95\% \\ -\dfrac{\Delta t}{17,520}, & \text{otherwise} \end{cases} \tag{28}$$

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where RH and T = hourly relative humidity and temperature over the measured period of Δt, respectively. Once fungal germination has occurred, the rate of mass loss (ML) is integrated over the subsequent time period, as shown in Eqs. (29) and (30)

$$\mathrm{ML}(t') = \int_{t\,\mathrm{at}\,\alpha=1}^{t'} \frac{\mathrm{ML}(\mathrm{RH}, T)}{dt} dt \tag{29}$$

$$\frac{\mathrm{ML}(\mathrm{RH}, T)}{dt} = -5.96 \times 10^{-2} + 1.96 \times 10^{-4} \cdot T + 6.25 \times 10^{-4} \cdot \mathrm{RH} \left[\frac{\%}{\mathrm{h}}\right] \tag{30}$$

where t = elapsed period from which $\alpha = 1$; and ML = mass loss that occurred during that period.

Structure

The model is deterministic and dynamic. Relative humidity is used as the describing parameter for moisture.

Biology

The extent of decay was measured by mass loss, which poses problems because reduction in structural capacity occurs prior to observable loss of material (Curling et al. 2000; Winandy and Morrell 1992; Curling et al. 2001). Two common European building decay fungi were used, *Coniophora puteana* and *Gloeophyllum sepiarium*.

Applicability

The model does not appear to be validated with field experiments, but is cross-referenced with hygrothermal simulations. Difficulties in measurement of very high relative humidity (e.g., 95%+) and reliability of material sorption isotherms at these higher ranges create some concerns on applicability of this model for in situ applications.

Institute for Research in Construction Fungal Decay Model

The Institute for Research in Construction (IRC) fungal decay model (Nofal and Kumaran 2011) is derived from the data provided by Viitanen and Ritschkoff (1991) and Viitanen (1997). The purpose was to provide a method to determine the damage, performance, and service life of building enclosure wood structural elements using mass loss as the indicator. Because wood-rotting fungi have a greater tolerance once established, the life cycle is divided into three stages: (1) initial response time, (2) critical growth conditions, and (3) survival conditions. For determination of the initial response time, a threshold relative humidity is established, shown in Eq. (31)

$$\mathrm{RH}_{\mathrm{crit}} = \begin{cases} -0.5T + 100, & T \leq 15°\mathrm{C} \\ 92.5\%, & T > 15°\mathrm{C} \end{cases} \tag{31}$$

The critical concern is mass loss, w_l caused by decay, showing the relationship between temperature T, relative humidity RH, and wood species W, provided in Eq. (32)

$$w_l = f(T, \mathrm{RH}, W) \cdot t + g(T, \mathrm{RH}, W) \tag{32}$$

Differentiation of the equation with respect to time provides the incremental mass loss over the recorded conditions. The time-dependent function, f, is described in Eq. (33), and the intercept, g, is defined in Eq. (34)

$$f(T, RH, W) = 0.1384T + 0.4370RH - 42.9450 + WS \cdot (0.0340T - 0.0210RH + 1.7210) \tag{33}$$

$$g(T, RH, W) = -2.227T - 0.0347RH + 0.0244T \cdot RH + WS \cdot (-0.504T + 0.0096RH + 0.0047T \cdot RH) \tag{34}$$

With respect to the lowest relative humidity for survival of the chlamydospores, the critical RH was found to be described by Eq. (35)

$$\mathrm{RH}_{\min} = 75 - 8.0703\exp\left(-0.5 \cdot \left(\frac{T - 17.2581}{3.5527}\right)^2\right) \tag{35}$$

With periods of insufficient humidity, the number of viable spores will slowly decrease. This can affect the speed at which fungal growth restarts upon return of suitable growing conditions. Species-specific recommendations are provided.

To relate the mass loss to the functional decrease in structural capacity, the relationship between a change in modulus of rupture (MOR) to mass loss was defined [Eq. (36)], where NQ represents the natural quality of wood

$$\mathrm{MOR}_{\mathrm{loss}} = 2.65w_l + 20.15 + \mathrm{NQ} \cdot (1.21w_l - 0.94) \tag{36}$$

Even at zero mass loss, the MOR is already reduced by ±20%.

Structure

The deterministic structure of this model is grounded on the cyclical and steady-state decay conditions collected by Viitanen (1991), and is thus not limited in the steady-state conditions derived in many of the other models. The partial derivatives $\partial f/\partial t$ and $\partial g/\partial t$ therefore model the rate of change in both temperature and relative humidity. The initial conditions pose a challenge to this model because the basis for mass loss suggests onset of damage occurs prior to any extent of fungal growth.

Biology

The equation uses mass loss as an indicator for decay. However, mass loss is a poor analogue for decay because significant ultrastructural changes occur in the incipient decay process (Curling et al. 2000; Winandy and Morrell 1992; Curling et al. 2001). Eq. (36), which is used to derive the reduction in modulus of rupture, is highly insensitive to initial mass loss. Relative humidity was used as the moisture metric of choice, likely due to limitations in the original data set. As Brischke and Rapp (2008) noted, the risks of decay are mainly governed by moisture contents exceeding the fiber saturation point, which all constitute as relative humidities between 97% and 100%. The accuracy of relative humidity to define decay is therefore uncertain.

Applicability

This model does not appear to have been used in field trials for validation. The extensive use of differential equations may position it as a more challenging equation for some practitioners. A greater repertoire of decay functions, f and g, may be required to characterize the properties of different materials, such as plywood and its

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different subtypes, and other engineered wood products (e.g., cross-laminated timber, orientated strand board, glulam).

Wood Degradation Model

The wood degradation model (Saito et al. 2008, 2012; Saito 2017) was developed from experimental studies of mass loss of *Pinus densiflora* experiencing decay by *Fomitopsis palustris* subjected to different temperature (from 5, 10, 20, 30, and 40°C) and humidity (93, 97, and 100%) conditions. It is unique in that this model includes the added moisture from metabolic decomposition of cellulose by decay fungi. Inclusion of this mechanism is important because the decay process could continue despite insufficiently high ambient relative humidity that would otherwise harbor fungal growth (Saito et al. 2008). The models make the following simplifying assumptions, mainly:

- the substrate is in instantaneous moisture equilibrium with its environment and the boundaries are adiabatic;
- fungal growth is immediate, and secondary metabolic by-products (O_2 and CO_2) have negligible impact on growth; and
- mass loss is directly correlated to fungal decomposition.

Fundamentally, mass loss, L, is defined by Eq. (37)

$$L = \frac{m_n - m_d}{m_n} \tag{37}$$

where m_n = mass of wood before decay; and m_d = mass of the wood after decay. The rate of mass loss at finite element i was assumed to begin when the critical humidity ratio, φ_c, within the wood pores was surpassed, shown in Eq. (38). Progression to adjacent finite elements, $i+1$, could only occur upon mass loss within the initial element, shown in Eq. (39)

$$\left.\frac{dL}{dt}\right|_{x=0} = k_m(\theta) \quad (\varphi_i > \varphi_c) \tag{38}$$

$$\left.\frac{dL}{dt}\right|_{x>0} = k_m(\theta) \quad (L_{i\pm 1} > 0;\ \varphi_i > \varphi_c) \tag{39}$$

The rate of mass loss was linearly regressed and found to equal a rate constant k_m, a function solely of temperature θ, shown in Eq. (40)

$$k_m(\theta) = (2.77 - 3.23\theta + 0.865\theta^2 - 0.0189\theta^3) \times 10^{-10} \tag{40}$$

The hygrothermal evaluation is achieved by coupled heat and mass transfer equation. Because wood rot produces nonnegligible moisture amounts from the decomposition of cellulose (Saito et al. 2008), an additional term, W_L, is added to the moisture balance equation [Eq. (41)]

$$W_L = h \cdot \rho_w \cdot \frac{dL}{dt} \tag{41}$$

where ρ_w = density of water; and h = moisture product ratio, corresponding to the ratio of moisture produced because of mass loss, and shown in Eq. (42). Due to difficulties in measuring metabolic activity, this ratio is determined experimentally. A value of 0.319 was determined for these experiments

$$h = \frac{d\varphi}{dL} \tag{42}$$

Structure

The deterministic structure of this model is founded on equations of mass and heat balance on the substrate, with a component for added water as a by-product of cellulose digestion by fungi. However, the rate constant of decay, determined by linear regression, only uses temperature as the primary variable. Moisture contents exceeding the fiber saturation point are known to accelerate decomposition (Zabel and Morrell 1992; Schmidt 2006). The simplifying assumptions of instantaneous substrate equilibration and fungal growth could pose challenges in applications when trying to predict time until start of decay.

Biology

The brown rot *Fomitopsis palustris* was used due to its controlled dispersion and use within the JIS K 1571 standard (JSA 2004). The wood samples were inoculated by placing them adjacent to the fungal culture on agar, separated by a resin mesh. It is possible that both spore and hyphal fragments could have been transferred as part of the inoculum, leading to accelerated growth over spore-only inoculation. It is uncertain how the inoculum load was controlled between samples. The wood species *Pinus densiflora* was selected as a non-decay-resistant wood, consequently leading to an overestimation of model results, thus permitting practitioners an added margin of safety.

Similar to other decay models, the driving metric is mass loss of the substrate. As previously discussed, the principal concern is the structural capacity of the substrate, which is already reduced prior to measurable mass loss.

Applicability

The model's underlying design permits estimation of decay based on constant conditions nearing the fiber saturation point of wood. However, because in situ conditions in buildings are subject to significant fluctuations, the predictive capacity of these models remain untested. Implementation of the finite-element hygrothermal equations requires direction on reasonable assumptions not found within these papers.

Discussion

The durability concerns posed by fungi are evidenced by the significant effort to quantify the risks. This review identified three main categories of fungal models: indexes, thresholds, and empirical models. Diverse disciplines have attempted to address mold concerns in buildings. Most models are deterministic in nature, but several authors have tried stochastic methods, and the need for more absolute terms of risk has resulted in limited adoption within the building science community. Within the surveyed models, the majority attempted to characterize surface mold growth, whereas only a few tried to assess structural reductions caused by decay. The cause for this is that decay generally follows the original wave of pioneering fungi, generally the surface molds (Zabel and Morrell 1992; Schmidt 2006).

Many of the models were challenged by the dynamic conditions experienced by fungi in real-world building enclosure applications. For laboratory experiments, steady-state conditions provide greater control of outputs and thus form the basis for most of the models, except for those models that incorporate oscillating temperature and humidity conditions or are based on field studies. Another issue is linearity. Most models assume that mold growth occurs at a linear pace given constant conditions until a steady state is achieved. Fungal growth is generally classified into three phases: germination, vegetative growth, and reproduction, as shown in Fig. 5; the rate of

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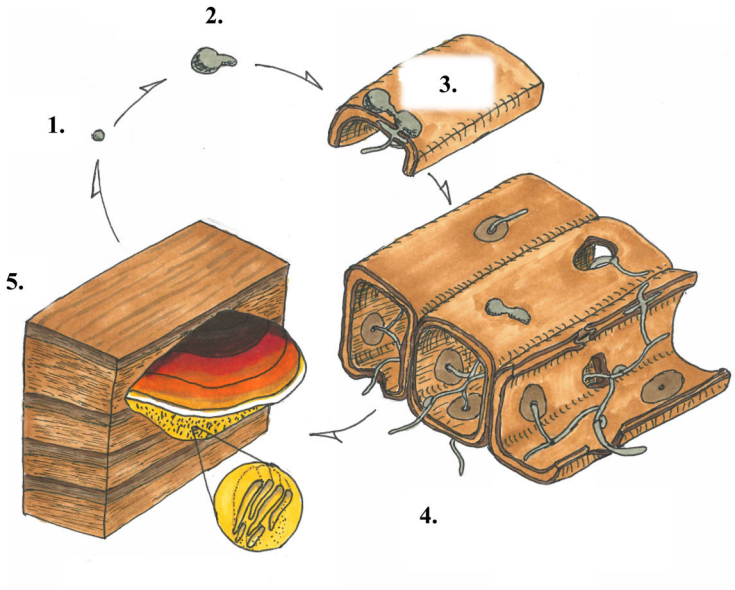
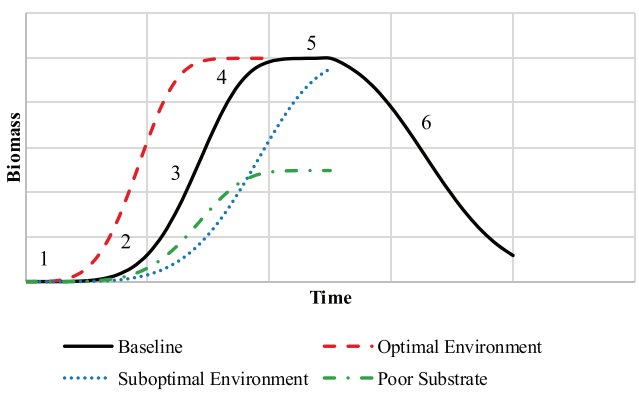


1: the spore swells and **2:** begins to germinate
3: the growth of an appressorium permits boring into the wood cell, with preliminary decay of the S2 cell wall cellulose.
4: vegetative growth, with hyphae decomposing the wood cell wall and expanding deeper into the wood superstructure.
5: the colonizing mycelium develops a basidiocarp, the fruiting body of the fungi, which releases spores through the pores of the hymenium.

Fig. 5. Life cycle for a hypothetical teleomorphic brown-rot fungi on a woody substrate.



1: lag phase;
2: acceleration phase;
3: exponential growth phase;
4: deceleration phase;
5: stationary phase;
6: death phase

Fig. 6. Typical sigmoidal growth curve of fungi including conceptual effects of optimal (dashed) and suboptimal (dotted) environments and nutrient poor (dashed-dotted) substrate according to Adan (1994).

growth is shown in Fig. 6. With the various growth stages of fungi and the nonlinear growth rates, many of the assumptions of linearity may not be valid.

Further, it is known that fungal growth is governed by suitable conditions for metabolic activity. There are a number of required conditions for fungal growth and survival (Zabel and Morrell 1992; Adan 1994).

- Water: Free water on the surfaces of cell lumina.
- Temperature: Optimum ranges from 15 to 45°C.
- Substrate nutrition: Digestible substrate that provides energy and metabolites.
- Chemical growth factors: Nitrogen compounds, vitamins, and essential elements.
- pH: Favorable pH range, preference for ranges between 3 and 6.
- Oxygen: Atmospheric oxygen at relatively low levels for most fungi and very low levels of chemical oxygen only for some microaerobic and facultative anaerobic fungi.
- Minimal antagonistic effects: A lack of biocides, nutrient competition, preservative treatments, extractives, ultraviolet radiation, or other toxins.

Generally, water, temperature, and substrate conditions have been considered by nearly all models, with the other factors generally being too tedious for measurement and inclusion within the model. However, the choice of metrics for water is somewhat contentious (Griffin 1977; Griffith and Boddy 1991; Block 1953; Adan 1994; van Laarhoven et al. 2015). Agriculture and food scientists have historically used water activity (a_w) to define the risk of fungal growth [see Skaar (1988) for further information]. By extension, relative humidity, which approaches the same value as water activity under steady-state conditions, has been adopted as an approximate analogue despite the use of dynamic conditions. Other metrics, such as water potential (φ), are used by plant pathologists but have not found broad acceptance due to unfamiliarity. Curiously, moisture content has only been used to model decay, despite recent research indicating that it can have a significant effect on surface mold growth on hygroscopic substrates and appears to behave independent from water activity (van Laarhoven et al. 2015). Consequently, the hygric properties of the substrate, especially in dynamic and cyclical environmental conditions, may play a larger role than originally thought.

Fungal growth is nearly impossible to model with any degree of certainty due to the stochastic nature of biological processes. While

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deterministic approaches can sufficiently approximate real-world stochastic conditions, a lack of resources prohibits the ability to sufficiently quantify the relationships with absolute confidence. Consequently, a limit-state approach, which defines the probabilistic failure enclosure at constant conditions and has been attempted but not fully realized by Isaksson et al. (2010), may be one potential route to resolve the nonlinear and stochastic processes of biodeterioration. Both a serviceability (mold), and ultimate (decay) state could provide a holistic approach to biodeterioration caused by fungi and may also yield a model suitable for other deteriorating agents as well. Finally, consideration of improved moisture metrics may be required to countenance the different effects of water activity (a_w) and moisture content or other water metrics in hygroscopic materials. With the biological roles of fungi, particularly interspecies competition mostly ignored within the literature, ecologic principles and approaches may prove useful in future work. Linear mixed-effects modeling may provide useful tools to account for the dynamic uncertainty with biological organisms in fluctuating conditions.

Conclusions

The durability and health concerns posed by fungi have resulted in extensive study to better understand the risks in buildings. This has led to a broad range of fungal modeling tools, both for molds and rot, which help better characterize the associated risks. Increased interest in high-performance homes and mass-timber structures further emphasizes the need to better understand moisture-related effects, particularly with respect to fungal growth.

This study reviewed 14 different models based on their mathematical structure, choice of variables, and biological merits. The diverse models can be approximately lumped into three approaches: indexes, which correlate environmental conditions to risk of mold growth; thresholds, which characterize the limiting environmental conditions and growth rates for fungal contamination; and empirical approaches, which use regressions from laboratory studies to infer time until germination and extent of contamination.

Many of the models require simplification, significant assumptions, or are unable to properly quantify the complexity of the interaction of living organisms in a dynamic environment. With these limitations, the accuracy of the models is uncertain, but they strongly indicate the need for further work in this area.

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