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Section 4 — Processes and Properties

# Limited variability in biological durability of thermally modified timber using vacuum based technology

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## ABSTRACT

The SmartHeat® thermal timber treatment is a new technology based on the process parameters being steered very precisely mainly due to the vacuum applied and heating system involved. Timber treated with this technology shows a potential for less variability of biological durability in one batch. Several batch treatments were sampled and assessed on statistical variability of decay resistance against Basidiomycetes and soft rotting micro-fungi according to lab testing as described in the standards CEN/TS 15083 part 1 and 2 respectively (only Basidiomycetes test results are reported in this paper). By means of Weibull distribution assessment it was possible to show that variability in biological durability of each treated beam is well controlled and that this variability is limited compared to natural durability of wood species. Lower treatment variability due to precise parameter control for each beam and limited deviations of process parameters within the treating vessel are considered the main contributing factors. The paper also states that lower control of process parameters of some heat treatment processes might induce higher variability of the obtained biological durability than a customer might expect.

**Keywords:** biological durability, thermal treatment, vacuum technology, variability

## 1. INTRODUCTION

In a previous IRG paper (Van Acker *et al.* 2010a) a methodology was presented on how to present the variation in natural durability. This paper intends to use this methodology for thermally modified timber and this option was earlier presented at the 5$^{th}$ European conference on Wood Modification in Riga (Van Acker *et al.* 2010b).

Thermal modification of wood has evolved over the last decades from laboratory-based research to commercially viable industrial processes. Thermal modification is invariably performed within a temperature range of 180°C to 260°C, with temperatures lower than 140°C resulting in only slight changes in material properties and higher temperatures mostly resulting in unacceptable degradation of the substrate (Hill 2006).
Hill (2006) summarized the result of thermally induced changes to the macromolecular constituents as altered physical and biological properties of the wood, with:

- improvement in dimensional stability;
- reduced hygroscopicity (lower EMC at a given RH);
- improved resistance to microbiological attack;
- an increase in modulus during the initial stages of heating, with a reduction thereafter;
- a reduction in impact toughness, modulus of rupture and work to fracture;
- reduced abrasion resistance;

- a tendency for crack and splits to form, knots to come loose and so on;
- darkening of the material.

Thermal modification or heat treatment intends to improve wood properties. Although changes in physical and mechanical properties are important (Bekhta and Niemz 2003), the increased biological durability is key for new industrial developments (Kamden *et al.* 2002, Tjeerdsma *et al.* 2002). A wide range of industrial productions of thermally modified timber has evolved (Militz 2002).

The need for a better quality control system was further underpinned by Welzbacher and Rapp (2002). They showed that protection against decay of wood that had been thermally modified by one of the four European commercial processes (Plato, ThermoWood, Retified wood or oil heat-treated wood) decreased in the order *Coniophora puteana* > *Coriolus (Trametes) versicolor* > *Oligoporus (Poria) placenta.* Although there was an improvement in biological durability, this was not as good as that achieved previously with laboratory heat-treated wood, showing that performance improvements were possible by producing a more homogeneous product, hence the need for better process control.

Based upon the need to control the heating of each individual plank the Dutch company Lignius developed the SmartHeat® process. This is a heat treatment process under vacuum that allows mass control during treatment. This paper is presenting more details on the advantage of this process for fit-for-purpose production of material with a homogeneous biological durability.

Cartwright and Findlay (1946) defined durability as the ability of a material or object to endure. The durability of timber includes, therefore, its resistance to fungal decay, to insect attack, to mechanical wear and to the destructive effects of exposure to all types of weather such as frost, sunshine, sandstorms, etc. The term biological durability can be used to identify the durability of wood and wood products determined by decaying organisms like fungi and insects. Natural durability is in many cases referred to as the intrinsic durability of a wood species or wood assortment. Wood preservation which concerns a treatment and enables to identify a dose response of active ingredients used to prevent or eradicate activity of decaying organisms like fungi and insects can be defined as enhanced, conferred or induced durability. Although thermal modification is not based on an active ingredient dose response the enhanced durability can be evaluated similarly. There is no specific reason to assess the performance of wood and wood products with regard to service life prediction of a commodity or building component differently whether durability is intrinsic or conferred. Hence it is useful to elaborate on the overall biological durability approach to assess wood product performance in view of service life prediction (Van Acker and Stevens 2000).

This paper makes reference to work on improved statistical approach of biological durability of wood related to outdoor uses in out of ground contact situations (Van Acker *et al.* 2010a). Starting with Weibull distribution functions of mass loss data obtained from worst case laboratory Basidiomycetes testing some parameters can be proposed which should be a better start for engineers to come to a comprehensive approach on variability and a probabilistic methodology for service life prediction.

The methodology to determine the natural durability of a wood species or the enhanced durability of modified wood is focussing only on fungal attack by Basidiomycetes. The option to work on a natural durability approach based on laboratory testing was earlier discussed (Van Acker *et al.* 1996). In this respect the European standard CEN/TS 15083-1 was developed to provide input for the overall natural durability standard EN 350. This methodology is based on earlier reported research by Van Acker *et al.* (1998, 1999 a, b).

According to EN 335 and ISO 21887 wood in use faces different possible decay mechanisms depending on the conditions of use and the relevant functional organisms related. ISO 21887 defines five use classes that represent different service situations to which wood and wood-based products can be exposed all over the world. Main concern is for the outdoor end uses.

Findlay (1985) summarized that it is usual to classify timber into five classes in respect to their durability (Table 1). In his table reproduced below the corresponding ‘life’ of a 2 x 2 inch stake, in average soil, is compared with the average loss in dry weight per cent suffered in laboratory tests.

***Table 1: Classes of natural durability of wood to fungal attack as defined by Findlay (1985)***

| Durability class | Life of test stake in the field, temperate, England | Life of test stake in the field, tropics, Fiji | Average loss in dry weight (%) |
|---|---|---|---|
| Very durable | Over 25 yr | Over 10 yr | Nil or negligible |
| Durable | 15-20 yr | 5-10 yr | Up to 5 % |
| Moderately durable | 10-15 yr | (not given) | 5-10 % |
| Non-durable | 5-10 yr | 2-5 yr | 10-30 % |
| Perishable | Less than 5 yr | Less than 2 yr | Over 30% |

Use class 4 (UC4) is defined as the condition of continuous soil or freshwater contact while UC3 is for outdoor uses without ground contact. Since the main difference is that soft rot fungi are not able to destroy wood under UC3 conditions there is clearly a difference in assessing performance, natural or conferred durability of wood and wood products. Therefore when focussing on applications related to UC3 it is not relevant to use results from ground contact service life testing. Hence natural durability classes as defined in EN 350 part 2 are not fully transferable to UC3 applications. Furthermore under UC3 a wide range of exposure conditions can be distinguished mainly different related to time of wetness induced.

A lot of valuable wood species are mainly used for use class 3 applications like window joinery, cladding, decking and garden furniture and it is of interest to obtain reliable data for calculating service life of such wood-based products anyhow.

Besides testing efficacy of wood preservatives interest is growing for better assessment of the biological durability of wood products in general. This is not only valid when assessing the natural durability of wood species but also to evaluate modified wood (thermal and chemical modifications) and other wood treatments that can hardly show a dose response (Van Acker and Stevens 2000).

Up to now both laboratory fungal testing to assess efficacy (e.g. EN 113 and EN 807) and testing natural durability (CEN/TS 15083-1&2) have only to a limited extent been able to use the results in a probabilistic way. The natural durability testing methodology as implemented now (CEN/TS 15083-1) only uses the median mass loss values of the Basidiomycetes fungus showing the highest mass loss figures to determine a durability class.

Durability classes as defined in EN 350 part 1 and 2 are intended as indicators for service life under specific conditions (outdoor uses in ground contact). Clearly the objective to translate such durability classes for end use out of ground contact (e.g. UC3) introduces several changes in coming to a time to failure assessment. Mainly the fact that besides insects the main wood destroying organisms are Basidiomycetes fungi and the fact that optimal conditions of wetness are mostly not present are two elements that need to be addressed when estimating how long a wood product will last under UC3 conditions.

## 2. EXPERIMENTAL METHODS

This paper is mainly dedicated to explore the option to use the outcome of fungal testing based on a natural durability approach for assessment of the variability as factor in modelling service life prediction for thermally modified wood (Van den Bulcke *et al.* 2008).

Several durability testing experiments were performed at the Laboratory of Wood Technology at the Ghent University on timber obtained from the company Lignius. The wood modified with the SmartHeat® thermal timber treatment was assessed on its biological durability against Basidiomycetes.

The results are compared with some selected natural durability reporting as presented by Van Acker *et al.* (2010a) originating from testing over the last 2 decades in the same laboratory. Both temperate and tropical wood species are included as well as some softwood species. Focus has been on those species where one or limited number of botanical species is concerned (commercial samples of timber can contain more than one botanical species) and a well defined origin could be identified. It should however be stated that the sampling was not intended to cover the whole wood species variability for each of the experiments and that sometimes merely a commercial sampling was assessed. According to CEN/TS 15083-1 test specimens shall originate from a minimum of three trees or shall be taken from a stock originally of more than 500 test specimens and originating from at least five planks or boards. The tests performed on the thermally modified timber were set up according the same guidelines.

The scope of CEN/TS 15083-1 is a method for determining the natural durability of a timber against wood-destroying basidiomycetes cultured on an agar medium. The method is applicable to all timber species. Test specimens used for Basidiomycetes fungal testing according to CEN/TS 15083-1 have a cross-section of (25 ± 0.5) mm x (15 ± 0.5) mm and are (50 ± 0.5) mm long. The nominal volume of each test specimen is 18.75 $cm^3$.

At least 30 test specimens for exposure to each test fungus should be used and they should be obtained from a minimum of five logs or planks. Additionally the test requires at least 10 moisture content test specimens (a minimum of one from each log or plank).
Virulence reference specimens from *Pinus sylvestris* sapwood should be used for testing softwoods and *Fagus sylvatica* for testing hardwoods. The validity of the test is based on minimum mass loss for the reference fungi.

The obligatory test fungi used and the test validity criteria are as follows:

- *Coniophora puteana* (Schumacher ex Fries) Karsten (BAM Ebw. 15) for soft- and hardwoods. Virulence test validity: Loss in mass of Scots pine sapwood and/or beech in 16 weeks: min. 30 %.
- *Poria placenta* (Fries) Cooke sensu J. Eriksson (FPRL 280) for softwoods. Virulence test validity: Loss in mass of Scots pine sapwood in 16 weeks: min. 20 %.
- *Coriolus versicolor* (Linnaeus) Quélet (CTB 863A) for hardwoods. Virulence test validity: Loss in mass of beech in 16 weeks: min. 20 %.

The test procedure has mass loss as a criterion for assessing organism attack and the standard requires oven-dry mass to be determined. However test specimens to be used in biological tests should not be oven-dried prior to the test. More details on the procedure operations are given in Van Acker *et al.* (2010a).

After exposure all specimens are oven-dried at 103 ± 2 °C until constant mass is obtained. The corrected mass loss is the difference between the calculated initial oven-dry mass (theoretical oven-dry mass using moisture content from extra specimens) and the final oven-dry mass of each test specimen.
The classification is based on the median mass losses determined for all the test specimens exposed to each of the test fungi. The natural durability of the wood species under test in the laboratory test should be classified in accordance with Table 2.

***Table 2: Classes of natural durability of wood to fungal attack using laboratory tests based on CEN/TS 15083-1***

| Durability class | Description | Result of laboratory tests expressed as median percentage mass loss |
|---|---|---|
| D1 | Very durable | m.l. ≤ 5 |
| D2 | Durable | m.l. > 5 but ≤ 10 |
| D3 | Moderately durable | m.l. > 10 but ≤ 15 |
| D4 | Slightly durable | m.l. > 15 but ≤ 30 |
| D5 | Not durable | m.l. > 30 |

The data for each combination of wood species and Basidiomycetes test were ranked and as such used for Weibull fitting (Weibull 1951). Significant Weibull distributions are expressed and graphically presented as a probability density and as a distribution function for each data set.

The Weibull probability density function can be presented as in the below equation (Eqn. 2):

$$f(x;\lambda,k) = \begin{cases} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k} & x \geq 0 \\ 0 & x < 0 \end{cases} \qquad (2)$$

where k > 0 is the shape parameter and λ > 0 is the scale parameter.

The value of *k* can be interpreted directly as follows:

- A value of *k*<1 indicates that the failure rate decreases over time. This happens if defective items fail early and the failure rate decreasing over time as the defective items are weeded out of the population.
- A value of *k*=1 indicates that the failure rate is constant over time. This might suggest random external events are causing failure.
- A value of *k*>1 indicates that the failure rate increases with time. This happens if there is an "ageing" process, or parts that are more likely to fail as time goes on.

For each data set the (cumulative) Weibull distribution function is described as follows (Eqn.3):

$$F(x;k,\lambda) = 1 - e^{-(x/\lambda)^k} \qquad (3)$$

Furthermore simple analysis allows calculating the median value Med(X) and e.g. quantiles at 0.1 (10 %) $r_{0,1}$ and at 0.9 (90%) $r_{0,9}$, meaning the level at which 10 % of the specimens showed lower or higher mass loss respectively. Additionally for the mass loss ranges as identified in table 2 the percentage of the wood that can be attributed to each durability class can be derived.

## 3. RESULTS AND DISCUSSION

The figures 1 to 8 detail results from Basidiomycetes testing according to CEN/TS 15083-1. Each figure contains a graphic representation of both the probability density and distribution function for each data set. In the related table below the graphs details are given on the median value Med(X), the quantiles $r_{0,1}$ and $r_{0,9}$, and percentages for each durability class using the mass loss ranges as in table 2. The rows in italic are not considered as outcome on durability according to the standard CEN/TS 15083-1 since they are not referring to the fungus showing the highest median mass loss value.

Figure 1 reports on natural durability of four tropical hardwood species and the softwood species Douglas fir (*Pseudotsuga menziesii*) and European larch (*Larix decidua*). These are all species commonly used or sometimes intended to be used for outdoor applications however not focussing on in ground contact situations. The tropical hardwoods curupixa (*Micropholis spp.*), tauari (*Couratari spp.*), sapelli (*Entandrophragma cylindricum*) and movingui (*Disthemonanthus benthamianus*)were all tested with *Coriolus versicolor*. Results for *Coniophora puteana* are not presented since significantly lower mass losses were recorded with this fungus. Curupixa shows some 30 % in D5 but still close to 10 % in D3 while over 50 % is in class D4. Tauari, sapelli, and movingui are predominantly showing material in D4 and even over 15 % in D3. The wide distribution of these species also implies over 5 % of the material is classified as D5. Movingui could be classified as D3 but higher proportions of the tested material are belonging to both D2 and D4, while significant amounts are D1 and D5. This but also the other ones presented here are clearly wood species with scope for probabilistic appraisal when considering service life prediction and focussing on a median mass loss of less than 15 % (D3) which might be somewhat misleading. The results for *Coniophora puteana* presented for both Douglas fir and European larch reveal that variability in fungal resistance of softwoods is surely not lower than for hardwood species.

Figures 2 up to 5 report on some results of thermally modified temperate hardwoods only for *Coriolus versicolor* (mass losses obtained for *Coniophora puteana* were anyhow lower), while figures 6 to 8 show data on thermally modified softwoods which are tested with the fungi *Coniophora puteana* and *Poria placenta*. Both the natural durability is presented as well as the enhanced durability induced by thermal modification according to the SmartHeat® thermal timber treatment. All batches were sampled as such that both untreated and modified material is fully comparable.

Ash (*Fraxinus excelsior*) (figure 2) shows a clear shift towards higher durability classes when modified. Process mass losses (PML) of approximately 10 and 15 % brings this material already in respectively D1 and classes D2/D3 independently of leaching according to EN84 of test specimens has been part of the test or not. A low percentage of material still in D3, D4 or D5 and the low $r_{0.9}$ indicate the minimal presence of lower durability material in the treated batches.
Both beech (*Fagus sylvatica*) and maple (*Acer pseudoplatanus*) (figure 3) allow for similar conclusions for treatment levels at 5-6 % and 13-14%. All treated material shows better

performance results both regarding the level of mass loss and the variability of the data when comparing with the tropical hardwood species natural durability as presented in figure 1.
Also birch (*Betula pendula & pubescens*) (figure 4) and poplar (*Populus spp.*) (figure 5), the last one being clearly a lower density hardwood, show that it is feasible to obtain thermally modified timber with very limited amount of lower durability material present. Both figure 4 on birch and figure 5 on poplar show data of each time two different test sets representing each time wood from different origin. Although for birch and poplar some differences between both sets could be detected the overall increased biological durability depending on a process mass loss level is clearly present. A process mass loss of over 14 % seems to lead to TMT material with nearly only D1 and D2 specimens present and $r_{0.9}$ lower than 10%.

Regarding the three thermally modified softwood species presented here: spruce (*Picea abies*) (figure 6), maritime pine (*Pinus pinaster*) (figure 7) and radiate pine (*Pinus radiata*) (figure 8) reference should be made to Douglas fir and larch in figure 1. Spruce treated at process mass loss levels of 2.8 and 6.7% allows classifying the product as respectively slightly better or significantly better than both reference species. Maritime pine (figure 7) and radiate pine (figure 8) shows that PML levels of 9 to 10% are required to get to durability levels which classifies the TMT material in D3 or higher. It needs to be stated that although *Coniophora puteana* is more virulent in decaying the non modified material it is clearly *Poria placenta* which becomes the critical fungus to assess biological durability according to the standard CEN/TS 15083-1. Similarly as for the low variability of modified temperate hardwoods also TMT softwood shows a higher degree of homogeneity than the biological durability of Douglas fir and European larch.

## 4. CONCLUSION

The methodology of the European standard CEN/TS 15083-1 uses median mass loss values recorded for the most degrading Basidiomycetes test fungus under worst case laboratory testing. This is a suitable factor to classify a sample of wood with regard to the resistance to decay either as evaluator for natural durability or enhanced durability due to thermal modification. Additional information can be obtained using the Weibull distribution and derived quantiles like those for 10% or 90%. Such results are more useful to indicate variability in expected service life. Furthermore the use of percentages attributed to different durability classes allows for a more probabilistic approach and clearly indicates to engineers to what extent thermally modified wood can be used as an alternative for medium durable tropical hardwood species or more durable softwood species. Data obtained for a range of wood species treated with the SmartHeat® thermal timber treatment clearly shows feasibility to treat timber to a durability level based on the indicator process mass loss with a contained variability and hence allows for producing material fit for purpose.

## 5. ACKNOWLEDGMENTS

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## REFERENCES


Bekhta, P. and Niemz, P. (2003). Effect of high temperature on the change in color, dimensional stability and mechanical properties of spruce wood. *Holzforschung*, **57**, 539-546

Burmester, A. (1973). Effect of heat-pressure treatments of semi-dry wood on its dimensional stability. *Holz als Roh- und Werkstoff*, 31(6),237-243.

Cartwright, K. and Findlay, W. (1946). *Decay of Timber and its Prevention*. HMSO London, 294 p.

Findlay, W. (1985). Preservation of timber in the tropics. Forestry Sciences. Martinus Nijhoff / dr. W. Junk publishers, Dordrecht. ISBN 90-247-3112-7, 273 p.

Hill, C.A.S. (2006). *Wood Modification – Chemical, Thermal and Other Processes*. John Wiley and Sons, Chichester, UK.

Kamden, D.P., Pizzi, A. and Jermanaud, A. (2002) Durability of heat treated wood. *Holz als Roh- und Werkstoff*, 60,1-6.

Militz, H. (2002). Thermal treatment of wood: European processes and their background. *International Research Group on Wood Preservation.* Document No. IRG/WP 02-40241.

Tjeerdsma, B, Stevens, M., Militz, H. and Van Acker, J. (2002). Effect of process conditions on moisture content and decay resistance of hydrothermally treated wood. *Holzforschung und Holzverwertung*, **4**(5), 94-96, 98-99.

Van Acker, J., Stevens, M., Van Cauwenberghe, T. and Seynaeve, T. (1996). Is laboratory testing of decay resistance questionable as a single criterion for natural durability? *International Research Group on Wood Preservation.* Document No. IRG 96-20096, 17 p.

Van Acker, J., Stevens, M., Carey, J., Sierra-Alvarez, R., Militz, H., Le Bayon, I., Kleist, G. and Peek, R-D. (1998). Cirteria for Basidiomycetes testing and ways of defining natural durability classes. *The International Research Group on Wood Preservation.* Document No. IRG/WP 98-20144.

Van Acker, J., Militz, H. and Stevens, M. (1999a). The significance of accelerated and laboratory testing methods for determining the natural durability of wood. *Holzforschung*, **53**, 449-458.

Van Acker, J., J. Carey, R. Sierra-Alvarez, I. Le Bayon, M. Grinda, H. Militz and R-D. Peek. (1999b). Laboratory testing of natural durability including Basidiomycetes and soil inhabiting micro-organisms. COST Action E2 - Final Conference 'Advances in wood preservation in Europe', EUR 19453 / ISBN 90-806565 1-8, paper 9, 13p.

Van Acker, J. and Stevens, M. (2000). Increased biological durability differs for traditional wood preservation and new non-biocidal systems (NBS). *The International Research Group on Wood Preservation*. Document No. IRG/WP 00-20212.

Van Acker, J., Van den Bulcke, J. and De Boever, L. (2010a). The biological durability approach for wood product performance and service life prediction. *The International Research Group on Wood Protection*, Document No. IRG/WP 10-20457.

Van Acker, J., Michon, S., De Boever, L., De Windt, I., Van den Bulcke, J., Van Swaay, B., and Stevens, M. (2010b). High quality thermal treatment using vacuum based technology to come to more homogeneous durability. Proceedings of the Fifth European Conference on Wood Modification (Ed. Hill, C., Militz, H. , Andersons, B.), 107-118.

Van den Bulcke, J., Van Acker, J. and Stevens, M. (2008). Service life prediction of wood: scale-dependent tools within a bio-engineering framework. *The International Research Group on Wood Protection.* Document No. IRG/WP 08-20387, 11p.

Weibull, W. (1951). A statistical distribution function of wide applicability, J. Appl. Mech.-Trans. ASME, **18**(3), 293–297.

Welzbacher, C.R. and Rapp, A.O. (2002). Comparison of thermally treated wood originating from four industrial scale processes – durability. *International Research Group on Wood Preservation*, Document No. IRG/WP 02-40229.

## STANDARDS

CEN/TS 15083-1&3 (2005): Durability of wood and wood-based products - Determination of the natural durability of solid wood against wood-destroying fungi, test methods - Part 1: Basidiomycetes, Part 2: Soft rotting micro-fungi.

EN 1001-2 (2005): Durability of wood and wood based products - Terminology - Part 2: Vocabulary

EN 113 (1996): Wood preservatives - Test method for determining the protective effectiveness against wood destroying basidiomycetes - Determination of the toxic values

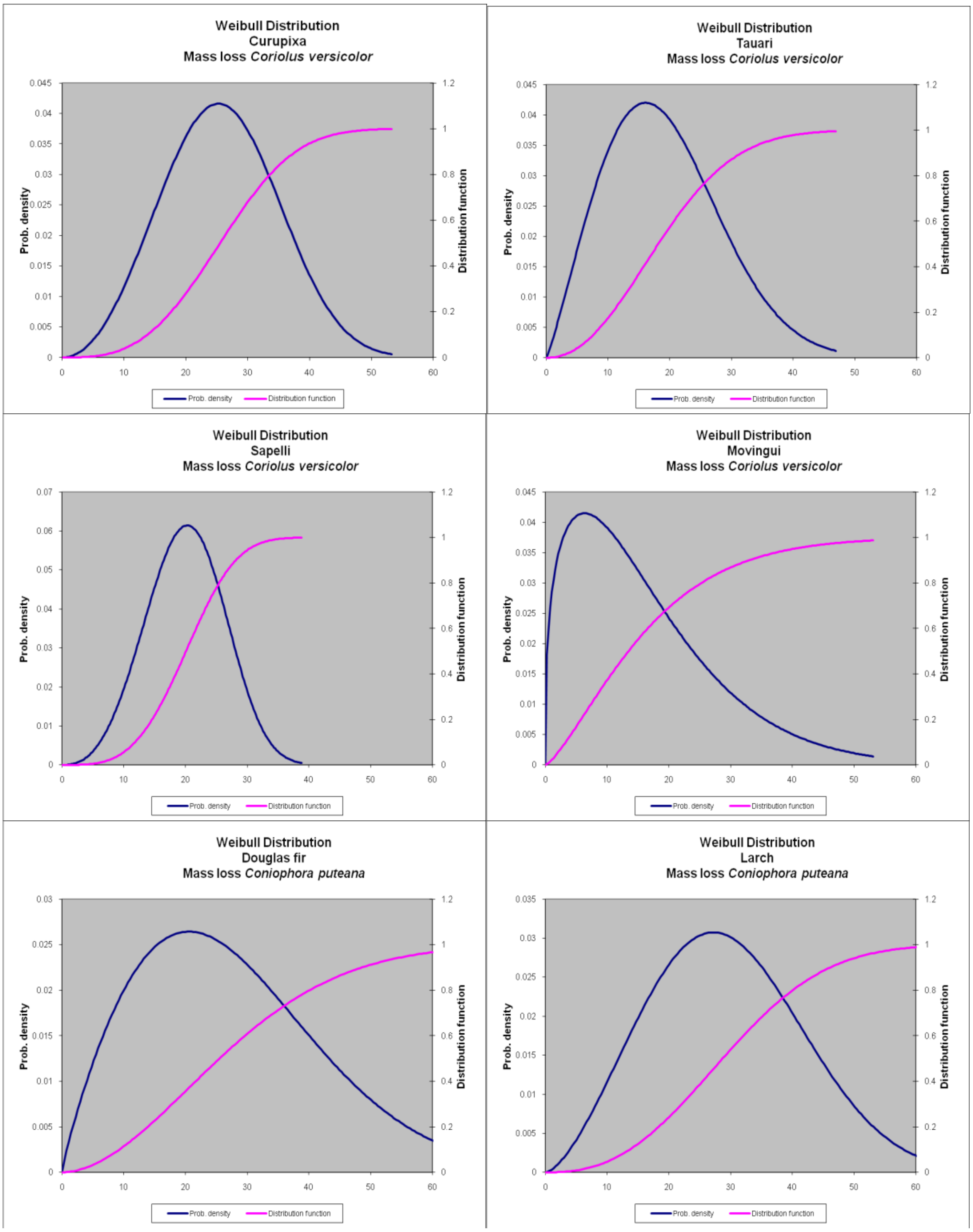
EN 335-1 (2006): Durability of wood and wood- based products - Definition of use classes - Part 1: General

EN 350-1 (1994): Durability of wood and wood-based products - Natural durability of solid wood - Part 1: Guide to the principles of testing and classification of the natural durability of wood

EN 350-2 (1994): Durability of wood and wood-based products - Natural durability of solid wood - Part 2: Guide to natural durability and treatability of selected wood species of importance in Europe

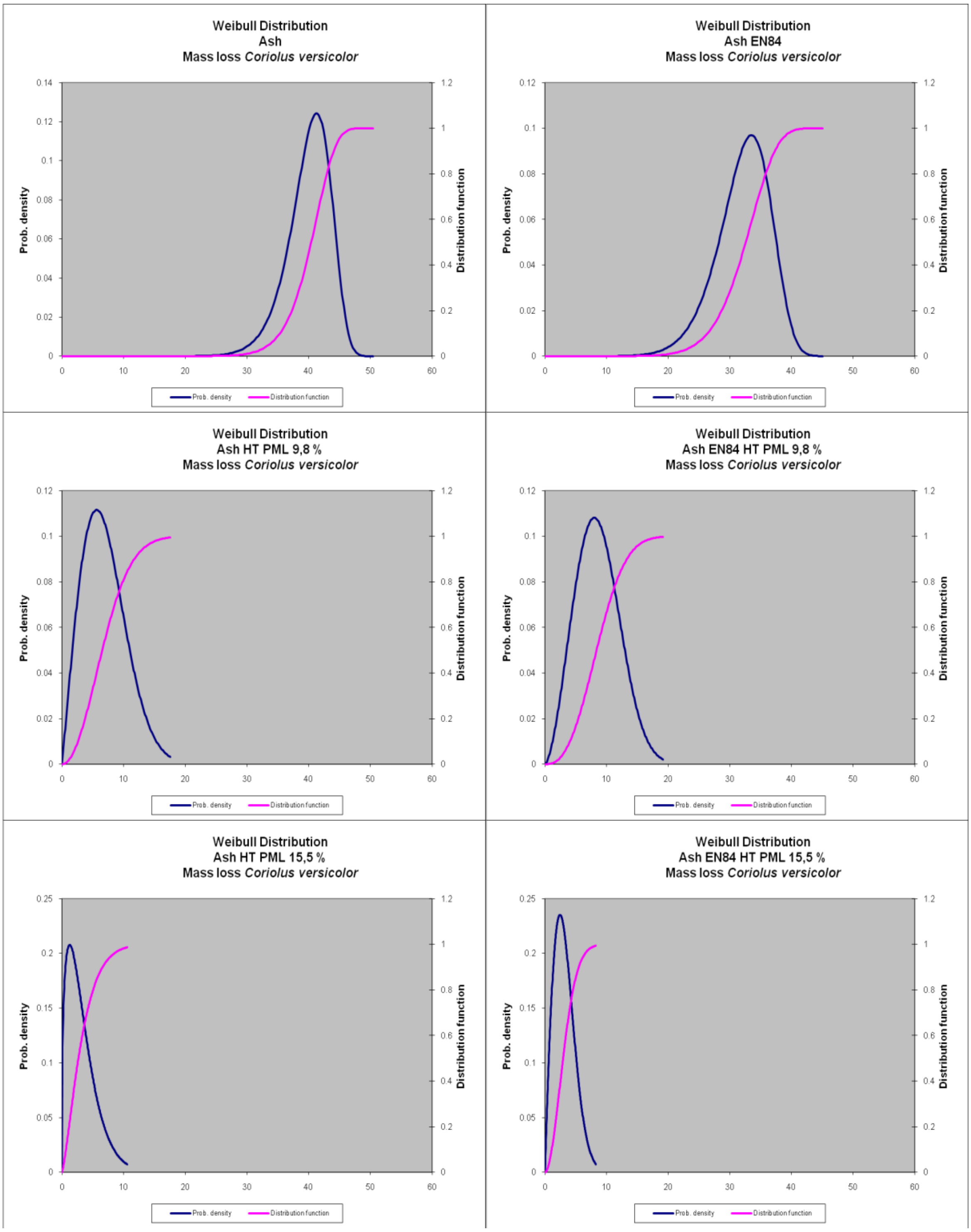
EN 84 (1997): Wood preservatives - Accelerated ageing of treated wood prior to biological testing - Leaching procedure

ISO 21887 (2007): Durability of wood and wood-based products -- Use classes



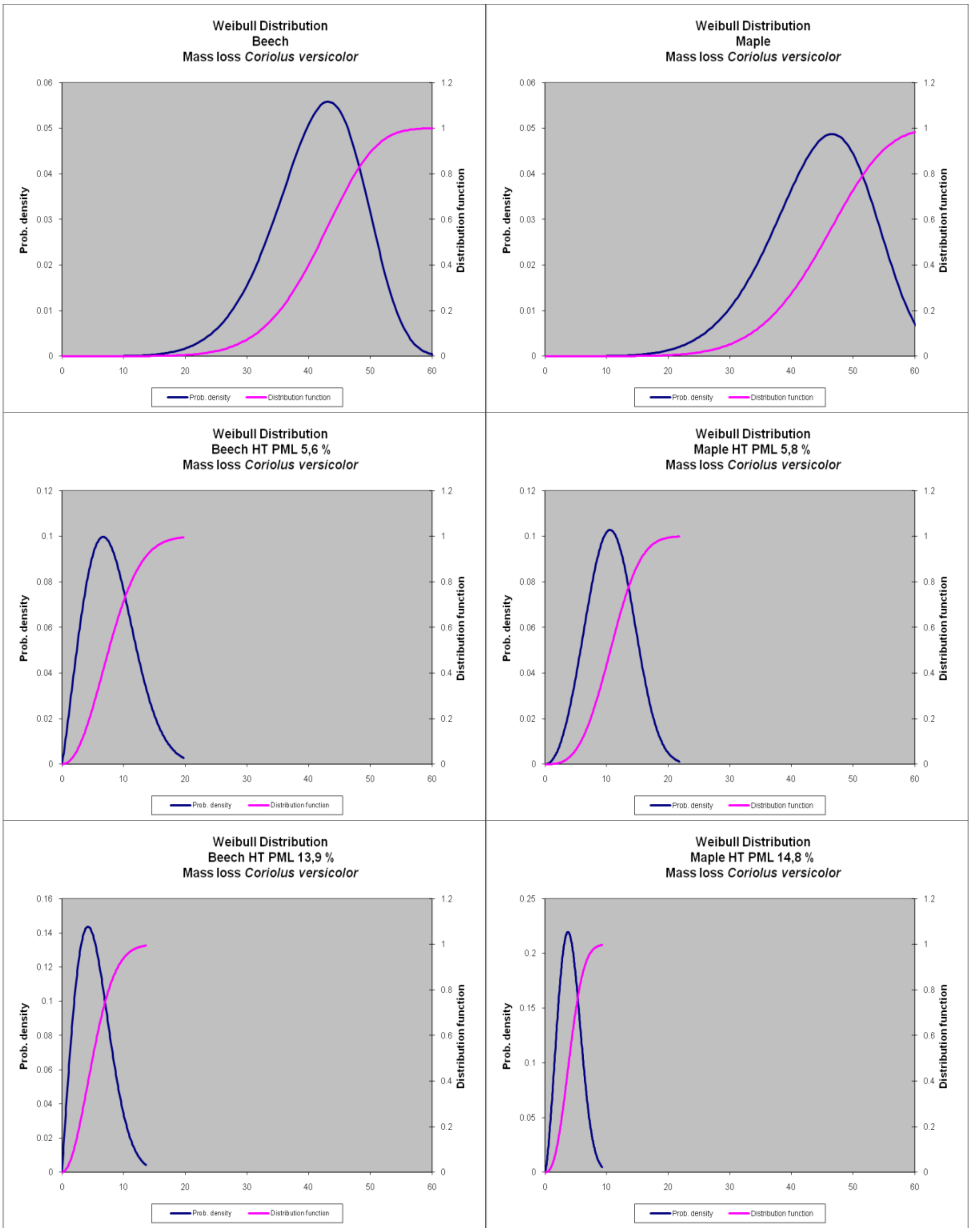

| Wood species | Fungus | Med(X) | $r_{0,1}$ | $r_{0,9}$ | %D1 | %D2 | %D3 | %D4 | %D5 |
|---|---|---|---|---|---|---|---|---|---|
| Curupixa | COR | 25.5 | 13.8 | 37.8 | 0.5 | 3.4 | 8.8 | **55.2** | **32.1** |
| Tauari | | 18.1 | 7.6 | 31.2 | 4.2 | 13.2 | 19.4 | **50.3** | 12.9 |
| Sapelli | | 20.1 | 11.8 | 28.2 | 0.5 | 5.1 | 16.1 | **72.7** | 5.6 |
| Movingui | | 13.5 | 3.3 | 33.0 | 16.8 | 20.4 | 17.9 | **31.7** | 13.2 |
| Douglas fir | CON | 25.5 | 9.3 | 48.6 | 3.3 | 8.1 | 11.3 | **38.2** | **39.1** |
| Larch | | 28.7 | 13.7 | 46.1 | 0.8 | 3.9 | 7.8 | **41.4** | **46.1** |

***Figure 1: Weibull distributions of mass loss (%, x-axis) and durability classes for medium durability tropical hardwoods (curupixa, tauari, sapelli, movingui) and for softwoods Douglas fir and European larch.***



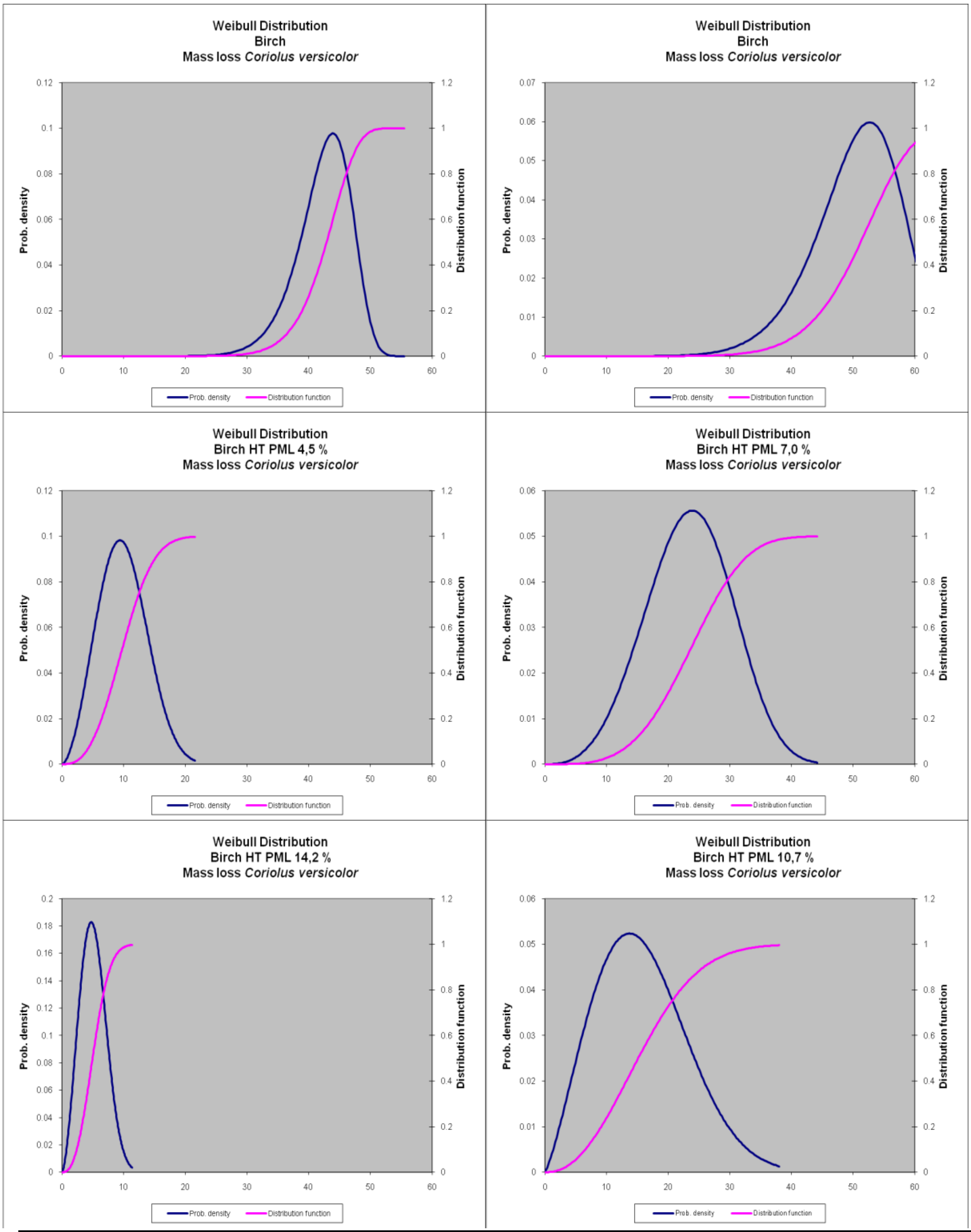

| Wood species | Fungus | Med(X) | $r_{0,1}$ | $r_{0,9}$ | %D1 | %D2 | %D3 | %D4 | %D5 |
|---|---|---|---|---|---|---|---|---|---|
| Ash | | 40.4 | 35.3 | 44.1 | 0.0 | 0.0 | 0.0 | 1.1 | **98.9** |
| PML 9.8 % | | 6.5 | 2.6 | 11.7 | **33.0** | **48.0** | 16.8 | 2.2 | 0.0 |
| PML 15.5 % | COR | 2.7 | 0.7 | 6.6 | **79.6** | 18.6 | 1.7 | 0.1 | 0.0 |
| Ash EN84 | | 32.6 | 26.4 | 37.3 | 0.0 | 0.0 | 0.1 | **28.2** | **71.8** |
| PML 9.8 % | | 8.4 | 4.1 | 13.3 | 16.4 | **50.1** | **29.2** | 4.3 | 0.0 |
| PML 15.5 % | | 3.0 | 1.1 | 5.5 | **85.2** | 14.7 | 0.1 | 0.0 | 0.0 |

***Figure 2: Weibull distributions of mass loss (%, x-axis) and durability classes for thermally modified ash***
***(both not leached and leached according to EN84)***



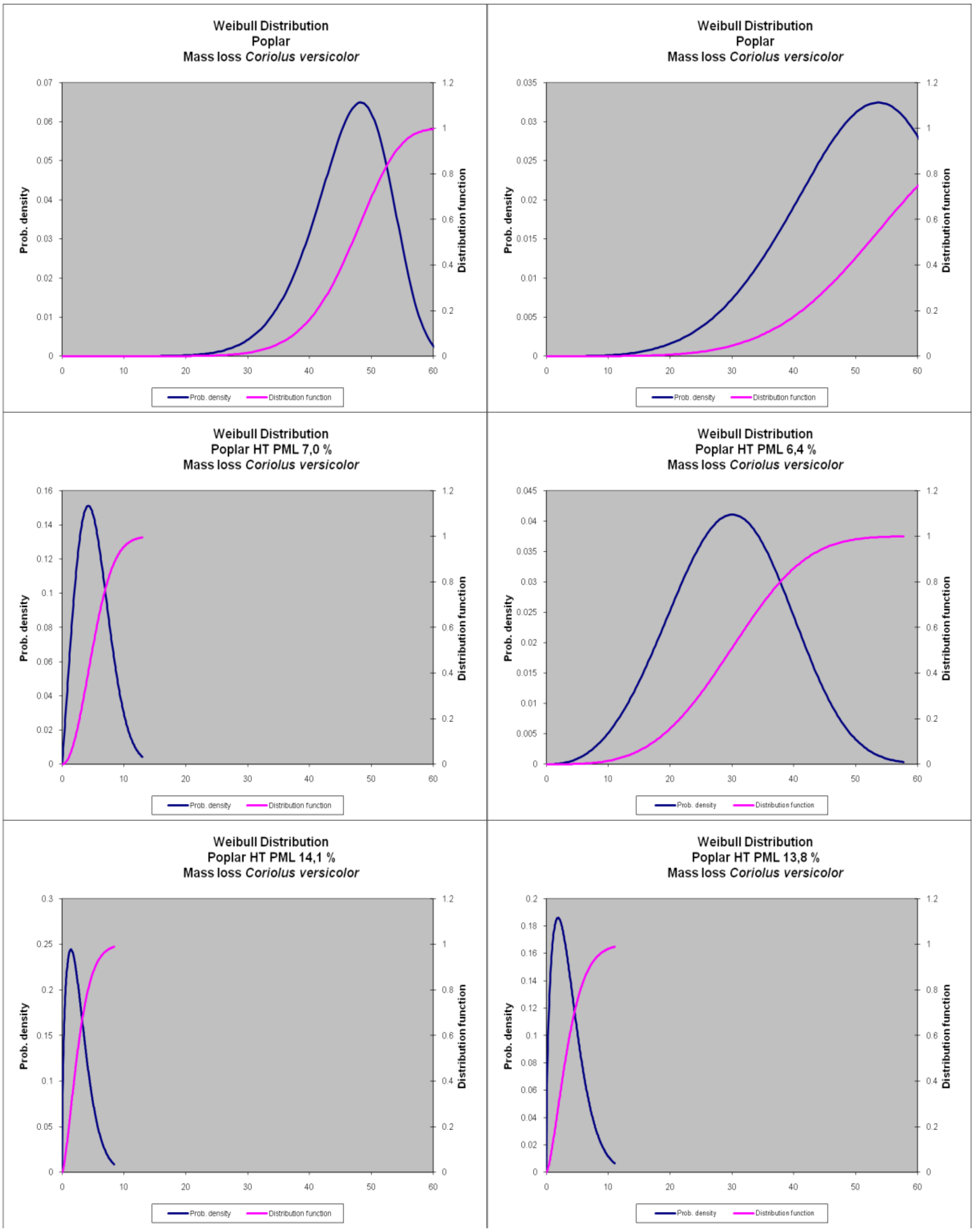

| Wood species | Fungus | Med(X) | $r_{0,1}$ | $r_{0,9}$ | %D1 | %D2 | %D3 | %D4 | %D5 |
|---|---|---|---|---|---|---|---|---|---|
| Beech | | 41.9 | 31.5 | 50.2 | 0.0 | 0.0 | 0.1 | 7.2 | **92.7** |
| PML 5.6 % | | 7.6 | 3.1 | 13.3 | **24.9** | **46.6** | **23.4** | 5.1 | 0.0 |
| PML 13.9 % | | 5.0 | 1.9 | 9.1 | **50.3** | **43.6** | 5.9 | 0.2 | 0.0 |
| Maple | COR | 45.2 | 33.5 | 54.8 | 0.0 | 0.0 | 0.1 | 5.1 | **94.8** |
| PML 5.8 % | | 10.6 | 5.9 | 15.6 | 6.2 | **37.3** | **43.6** | 12.9 | 0.0 |
| PML 14.8 % | | 4.0 | 1.9 | 6.4 | **70.8** | **29.1** | 0.1 | 0.0 | 0.0 |

***Figure 3: Weibull distributions of mass loss (%, x-axis) and durability classes for thermally modified beech and maple***



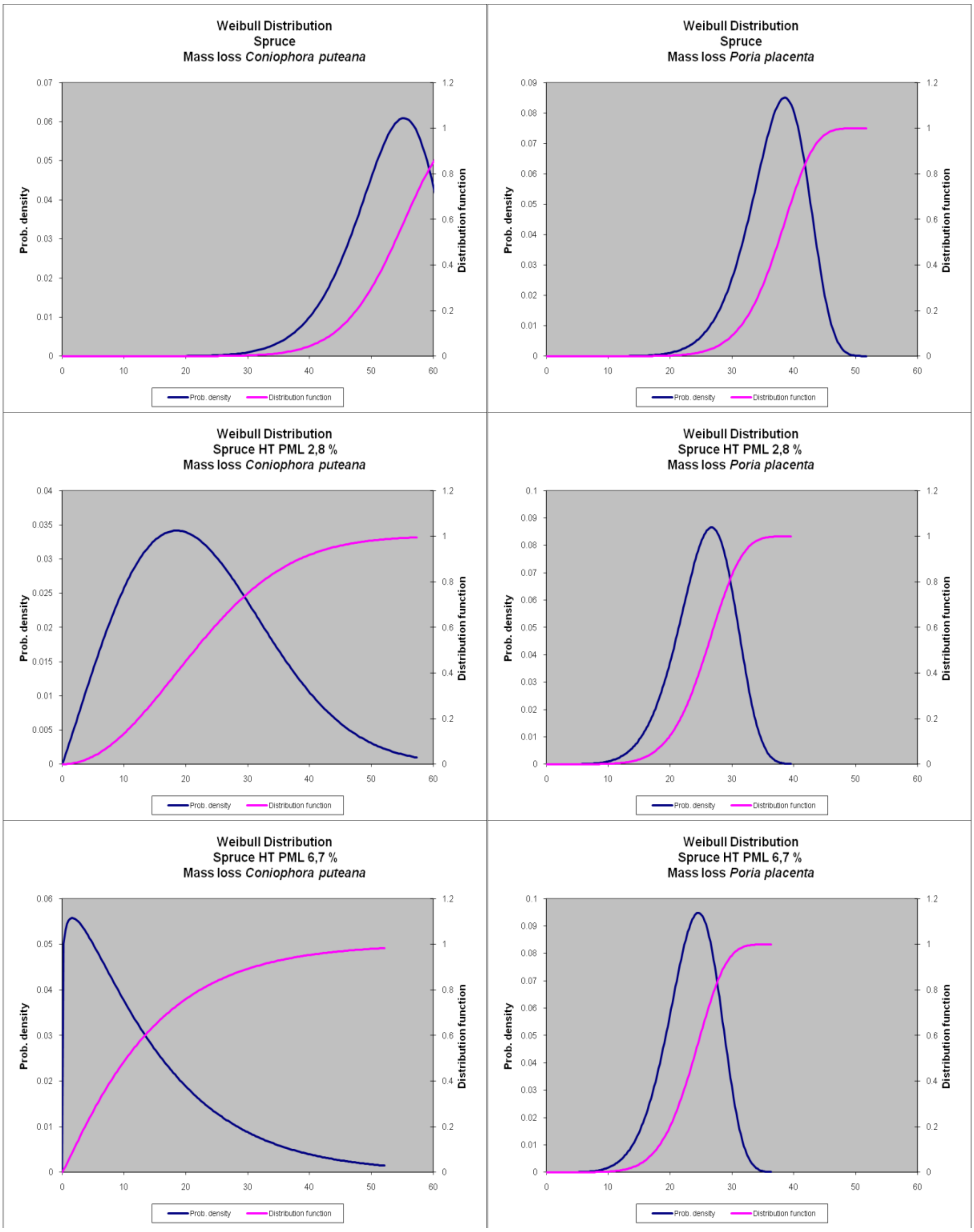

| Wood species | Fungus | Med(X) | $r_{0,1}$ | $r_{0,9}$ | %D1 | %D2 | %D3 | %D4 | %D5 |
|---|---|---|---|---|---|---|---|---|---|
| Birch set 1 | COR | 42.9 | 36.5 | 47.5 | 0.0 | 0.0 | 0.0 | 1.1 | **98.9** |
| PML 4.5 % | | 9.7 | 4.9 | 15.0 | 10.6 | **42.2** | **37.0** | 10.2 | 0.0 |
| PML 14.2 % | | 5.0 | 2.4 | 7.9 | **50.6** | **48.0** | 1.4 | 0.0 | 0.0 |
| Birch set 2 | | 51.2 | 41.2 | 58.9 | 0.0 | 0.0 | 0.0 | 0.7 | **99.3** |
| PML 7.0 % | | 23.5 | 14.3 | 32.4 | 0.2 | 2.5 | 9.2 | **70.4** | 17.7 |
| PML 10.7 % | | 15.1 | 6.6 | 25.8 | 5.5 | 18.3 | **25.5** | **46.8** | 3.9 |

***Figure 4: Weibull distributions of mass loss (%, x-axis) and durability classes for thermally modified birch (set 1: left; set 2: right)***



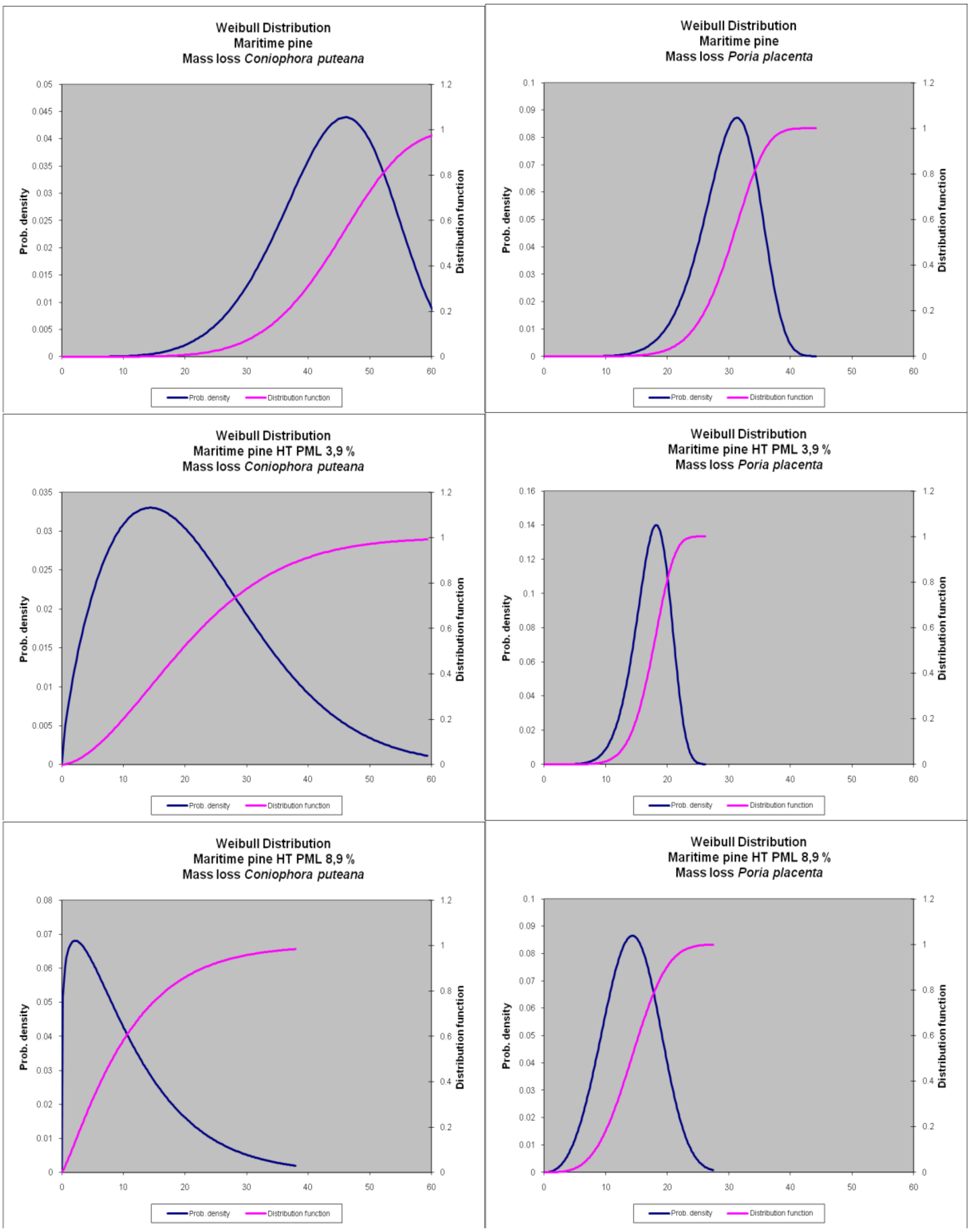

| Wood species | Fungus | Med(X) | $r_{0,1}$ | $r_{0,9}$ | %D1 | %D2 | %D3 | %D4 | %D5 |
|---|---|---|---|---|---|---|---|---|---|
| Poplar set 1 | COR | 46.9 | 37.7 | 54.0 | 0.0 | 0.0 | 0.0 | 1.5 | **98.5** |
| PML 7.0 % | | 4.9 | 2.0 | 8.7 | **51.7** | **43.7** | 4.5 | 0.1 | 0.0 |
| PML 14.1 % | | 2.4 | 0.7 | 5.3 | **87.6** | **12.1** | 0.3 | 0.0 | 0.0 |
| Poplar set 2 | | 52.2 | 35.4 | 66.8 | 0.0 | 0.0 | 0.1 | 4.5 | **95.4** |
| PML 6.4 % | | 29.8 | 17.5 | 41.9 | 0.1 | 1.3 | 4.5 | **44.9** | **49.1** |
| PML 13.8 % | | 3.1 | 0.9 | 7.0 | **75.2** | **22.8** | 1.9 | 0.1 | 0.0 |

***Figure 5: Weibull distributions of mass loss (%, x-axis) and durability classes for thermally modified poplar (set 1: left; set 2: right)***



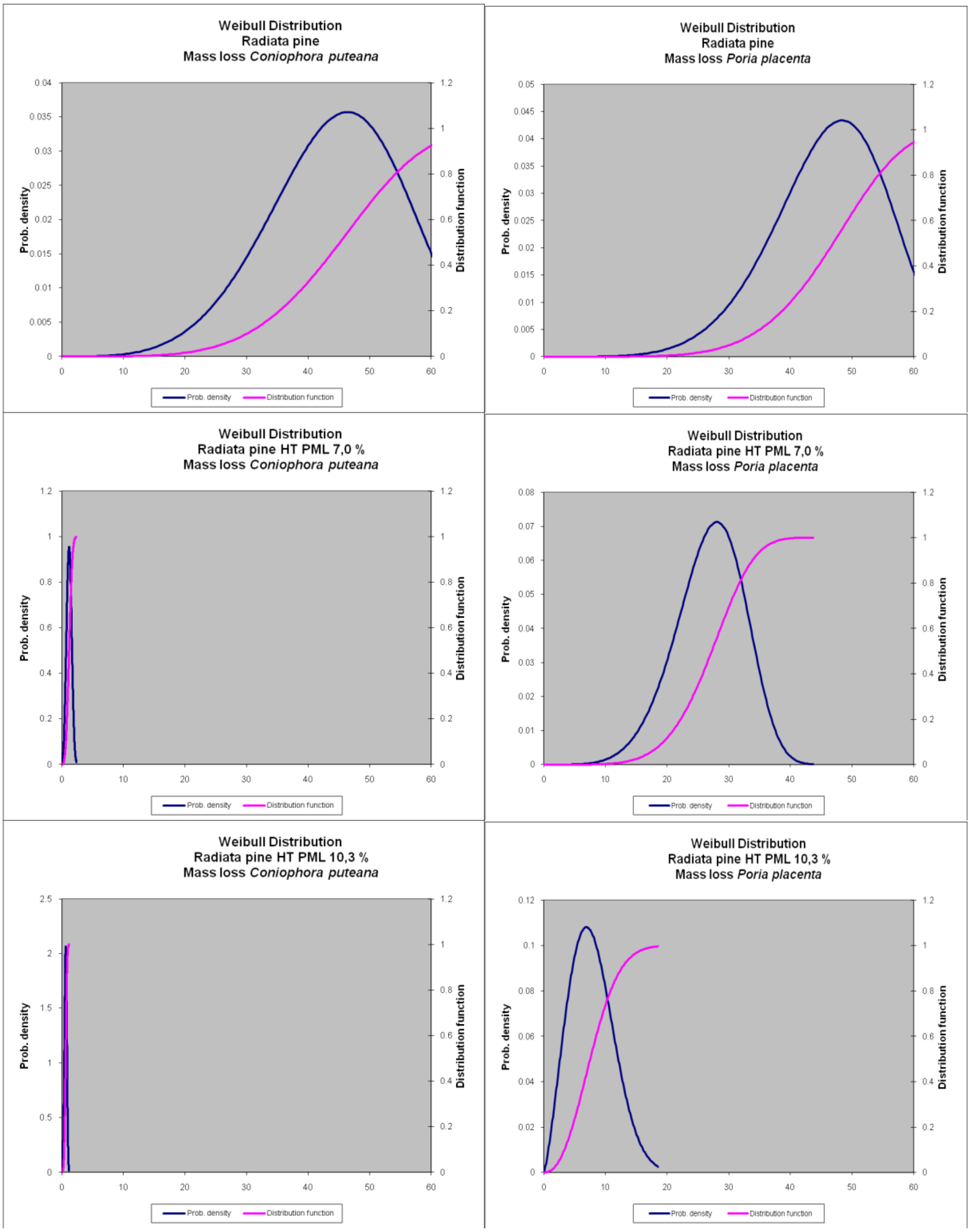

| Wood species | Fungus | Med(X) | $r_{0,1}$ | $r_{0,9}$ | %D1 | %D2 | %D3 | %D4 | %D5 |
|---|---|---|---|---|---|---|---|---|---|
| Spruce | CON | 53.8 | 43.8 | 61.3 | 0.0 | 0.0 | 0.0 | 0.3 | **99.7** |
| | POR | *37.5* | *30.4* | *42.9* | *0.0* | *0.0* | *0.0* | *8.9* | *91.1* |
| PML 2.8 % | CON | *21.4* | *8.6* | *38.4* | *3.4* | *10.0* | *14.9* | *46.7* | *25.0* |
| | POR | 25.9 | 19.3 | 31.3 | 0.0 | 0.1 | 2.0 | **80.9** | 17.0 |
| PML 6.7 % | CON | *10.4* | *1.9* | *30.9* | *26.7* | *21.9* | *16.1* | *24.6* | *10.7* |
| | POR | 23.8 | 17.8 | 28.7 | 0.0 | 0.3 | 3.2 | **91.7** | 4.8 |

***Figure 6: Weibull distributions of mass loss (%, x-axis) and durability classes for thermally modified spruce***




| Wood species | Fungus | Med(X) | $r_{0,1}$ | $r_{0,9}$ | %D1 | %D2 | %D3 | %D4 | %D5 |
|---|---|---|---|---|---|---|---|---|---|
| Maritime pine | CON | 44.7 | 31.9 | 55.3 | 0.0 | 0.0 | 0.1 | 7.1 | **92.8** |
| | POR | *30.4* | *23.7* | *35.7* | *0.0* | *0.0* | *0.3* | *46.2* | *53.4* |
| PML 3.9 % | CON | 19.2 | 6.4 | 38.7 | 6.6 | 13.5 | 16.2 | **41.1** | **22.6** |
| | POR | *17.7* | *13.5* | *21.0* | *0.0* | *1.3* | *18.5* | *80.2* | *0.0* |
| PML 8.9 % | CON | *8.2* | *1.6* | *22.9* | *32.2* | *26.1* | *17.2* | *20.3* | *4.2* |
| | POR | 14.2 | 8.3 | 19.9 | 1.7 | 16.5 | **38.8** | **43.1** | 0.0 |

***Figure 7: Weibull distributions of mass loss (%, x-axis) and durability classes for thermally modified maritime pine***




| Wood species | Fungus | Med(X) | $r_{0,1}$ | $r_{0,9}$ | %D1 | %D2 | %D3 | %D4 | %D5 |
|---|---|---|---|---|---|---|---|---|---|
| Radiata pine | CON | *45.2* | *30.1* | *58.6* | *0.0* | *0.1* | *0.4* | *9.5* | *90.1* |
| | POR | 46.9 | 33.9 | 57.7 | 0.0 | 0.0 | 0.1 | 4.9 | **95.0** |
| PML 7.0 % | CON | *1.2* | *0.7* | *1.7* | *100* | *0.0* | *0.0* | *0.0* | *0.0* |
| | POR | 27.2 | 19.4 | 33.8 | 0.0 | 0.3 | 2.2 | **66.8** | **30.7** |
| PML 10.3 % | CON | *0.6* | *0.4* | *0.9* | *100* | *0.0* | *0.0* | *0.0* | *0.0* |
| | POR | 7.5 | 3.3 | 12.6 | **23.5** | **50.3** | **23.0** | 3.2 | 0.0 |

***Figure 8: Weibull distributions of mass loss (%, x-axis) and durability classes for thermally modified radiata pine***