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30 credits

Factors affecting the development of surface mould growth on untreated wood

Faktorer som påvirker vekst av svertesopp på ubehandlet tre

Solrun Karlsen Lie

Preface

This thesis marks the end of my Master’s degree of Science in Structural Engineering and Architecture with specialization in wood technology at the Norwegian University of Life Sciences (NMBU), Department of Matematical Sciences and Technology (IMT). This master’s thesis is submitted at NMBU, Department of Ecology and Natural Resource Management (INA). The work presented in this thesis is a part of the research project “Increased use of wood in urban areas – WOOD/BE/BETTER”, and costs related to this thesis have been funded by the Research Council of Norway through the project. The institutions mentioned above are sincerely thanked for making the work presented in this thesis possible.

I am very grateful to all contributors to this project. My supervisors Prof. Geir Isak Vestøl (NMBU), Dr. Lone Ross Gobakken (Norsk institutt for bioøkonomi – NIBIO) and Prof. Thomas Kringlebotn Thiis (NMBU) have given valuable help with both test design and guidance through the writing process. Senior engineer Eva Grodås (NIBIO) and PhD candidate Kärt Kängsepp (NIBIO) have been a pleasure to collaborate with during the laboratory work. Senior engineer Sigrun Kolstad (NIBIO) made the spore suspension and Senior engineer Lars Morten Opseth (The centre for plant research in controlled climate - SKP) managed the climatic chambers used in the laboratory work.

I would like to express my special gratitude towards Geir and Lone who have contributed greatly to this thesis by giving very skilful and patient guidance and inspiring me with their knowledge and dedication.

Finally, I would like to thank my family for the support and my friends for making the study period an adventure.

Ås, December 2015.

Solrun Karlsen Lie

Abstract

A successful use of untreated wood as facade material requires knowledge about how the appearance develops over time. Surface moulds greatly affect the appearance of untreated wood, and even more knowledge about the critical levels and interactions of the factors affecting mould growth is required to predict the mould growth more accurately on materials exposed outdoors.

The aim of this study was to investigate the development of surface mould growth and moisture content on untreated wood exposed to different temperature, relative humidity and wetting periods. Wood properties that were investigated are heartwood/sapwood and density.

Specimens of aspen (*Populus tremula* (L.)), Scots pine (*Pinus sylvestris* (L.)) and Norway spruce (*Picea abies* (L.) Karst) were exposed to eight climatic conditions with two different levels of relative humidity (65 and 85 %), temperature (10 and 25 °C) and wetting period (2 and 4 hours). The specimens in the climates set at 85 % RH were exposed for 91 days, and the specimens in the climates set at 65 % RH were exposed for 119 days. To investigate the development of wood moisture content and mould growth, the specimens were weighed and the degree of mould growth on each specimen was visually evaluated once a week during the exposure period.

Analysis showed that exposure time, wood moisture content, relative humidity, wetting period, wood species and heartwood/sapwood were factors that significantly affected the mould growth. Increased wood moisture content increased the mould growth rate. The effect of temperature was only significant for the development of surface mould growth on spruce. Lowering the temperature decreases the wood drying rate and this may have counteracted the effect of a higher temperature on the moulds metabolism. Aspen and pine sapwood were most susceptible to mould growth. Pine heartwood and spruce heartwood were least susceptible to mould growth. Heartwood was significantly less susceptible to mould growth for both pine and spruce. Aspen was the only species where density affected the mould growth, but the heartwood proportion of the specimens of aspen was not known. Uncertainties regarding the actual climatic conditions made it challenging to draw conclusions about critical levels of the factors.

Sammendrag

Vellykket bruk av ubehandlet tre som fasademateriale krever kunnskap om hvordan fasadens utseende endrer seg over tid. Svertesopp kan ha stor betydning for dette, og vi trenger mer kunnskap om kritiske nivåer og interaksjoner mellom faktorene som påvirker soppveksten for å mer presist kunne forutse svertesoppvekst på materialer eksponert utendørs.

Målet med denne studien var å undersøke utviklingen av svertesopp og fuktighetsinnhold på ubehandlet tre ved ulik temperatur, relativ luftfuktighet og våttid. Virkesegenskaper som er undersøkt er kjerneved/yteved og densitet.

Prøver av osp (*Populus tremula* (L.)), furu (*Pinus sylvestris* (L.)) og gran (*Picea abies* (L.) Karst) ble eksponert for åtte klimaer med to ulike nivåer av relativ luftfuktighet (65 og 85 %), temperatur (10 og 25 °C) og våttid (2 og 4 timer). Forsøket varte i 91 dager for prøvene i klimaene innstilt på 85 % relativ luftfuktighet, og i 119 dager for prøvene i klimaene innstilt på 65 % relativ luftfuktighet. Prøvene ble veiet og visuelt evaluert for grad av svertesoppvekst en gang per uke, for å undersøke utviklingen av fuktighetsinnhold og soppvekst over tid.

Analysene viste at eksponeringstid, trevirkets fuktighetsinnhold, relativ luftfuktighet, våttid, treslag og kjerneved/yteved hadde en signifikant påvirkning på svertesoppveksten. Økt fuktighetsinnhold økte veksten. Temperaturen hadde kun signifikant effekt for svertesoppveksten på gran. Lavere temperatur fører til at trevirket tørker saktere og dette kan ha jevnet ut effekten av høyere temperatur på soppens metabolisme. Osp og furu yteved hadde mest svertesoppvekst, og furu kjerneved og gran kjerneved hadde minst svertesoppvekst. Kjerneved hadde signifikant mindre svertesoppvekst enn yteved for både furu og gran. Osp var eneste treslag hvor densiteten hadde en signifikant effekt for svertesoppveksten, men kjernevedandelen for osp var ikke kjent. Usikkerheter rundt faktiske forhold i klimaene gjorde det utfordrende å trekke konklusjoner rundt kritiske nivåer for de ulike faktorene.

Contents

Abbreviations and definitions

ChiSquare	lists the Wald tests for the hypothesis that each of the parameters is zero. Computed as (Estimate/Std error)^2
Climate	Climatic chamber
DF	degrees of freedom
h	hour(s)
L-R Chisquare	lists the likelihood-ratio test of the hypothesis that the corresponding parameter is zero, given other terms in the model
MC	wood moisture content (%)
Misclassification Rate	the rate for which the response category with the highest fitted probability is not the observed category. A smaller value indicates a better fit
p-value	the probability of getting a test result equal to or more extreme than what was actually observed, given that the null hypothesis is true
R^2	coefficient of determination. Proportion of the total uncertainty that is attributed to the model fit. Values closer to 1 indicates a better fit
RH	relative humidity (%)
RMSE	root mean square error. Smaller values indicate a better fit
SD	standard deviation
Std Error	standard error
T	temperature (°C)
TOW	time-of-wetness
Wood material	species and eventual sapwood/heartwood

1 Introduction

Untreated wood as a facade material can be environmentally friendly, cost effective and easy to maintain, which is a requirement for today's building materials (Larsen and Mattsson 2009). Wood is a renewable resource and the use of wood helps lowering the greenhouse effect. Wood materials stores carbon during its service life; increased use of wood and increasing the service life will therefore increase the amount of stored carbon (Gobakken et al. 2014). Untreated wood avoids the use of chemical agents for surface treatment and there is no maintenance such as washing and renewing the surface treatment.

Wooden materials that are produced locally should be used to maintain the positive environmental effect. In Norwegian forests, the growth is greater than the harvesting, and Norwegian forests are managed according to the principles for a sustainable forestry (Svanæs 2004). Raknes (1996) recommends heartwood of Scots pine (*Pinus sylvestris* (L.)), Norway spruce (*Picea abies* (L.) Karst) and aspen (*Populus tremula* (L.)) as untreated wooden cladding. Pine heartwood is described as the safest choice, and aspen the most questionable. Oak heartwood (*Quercus* (L.)) and larch heartwood (*Larix decidua* Mill.) have been increasingly used in recent years but are less common in Norway, resulting in more import and transport over longer distances and this reduces the environmental advantage (Larsen and Mattson 2009).

In addition to the environmental benefits, aesthetic causes are often the reason for choosing untreated wooden claddings. Due to weathering, the visual appearance of untreated wood develops over time; the colour gradually changes towards grey or brown, and cracking and warping of the panel may occur. Hirche (2014 p. 11) defined weathering as "the general term for weather-induced changes on surfaces". Weathering is affected by sunlight, temperature, moisture content, washing by rain, abrasion by windblown particles and biological attack by microorganism (Williams et al. 2000). Surface moulds are biological agents that highly contribute to the colour change of wood caused by weathering.

Predicting the development of surface mould growth is important to avoid unwanted surprises regarding the visual appearance of a facade. Climate changes are expected in the future, and this may also cause a different appearance than in today's climate. Increased knowledge about what affects the development of surface mould growth on untreated wood can contribute to increased use of it as a building material.

1.1 Surface moulds

In this thesis, surface moulds are used as a term for discolouring fungi growing on wooden surfaces, including moulds and blue-stain in service. Surface moulds mainly affect the visual aspect of the wood, and have no significant impact on the strength properties (Schmidt 2006). Surface moulds on wood consist of coloured spores or hyphae, which appear in a speckled or more uniform pattern (Figure 1). The colour of moulds can be black, grey, green, purple and red (Zabel and Morrell 1992). Blue-stain in service, mildew and discolouring fungi have mainly dark coloured hyphae and spores (Gobakken 2009). *Aureobasidium pullulans* is one of the most dominating mould species occurring on outdoor building materials (Gobakken 2009; Rüther 2011), and species from the following genus are also commonly growing on building materials: *Aspergillus*, *Chaetominum*, *Cladosporium*, *Penicillum*, *Stachybotrys*, *Trichoderma and Ulocladium* (Mattsson 2004).

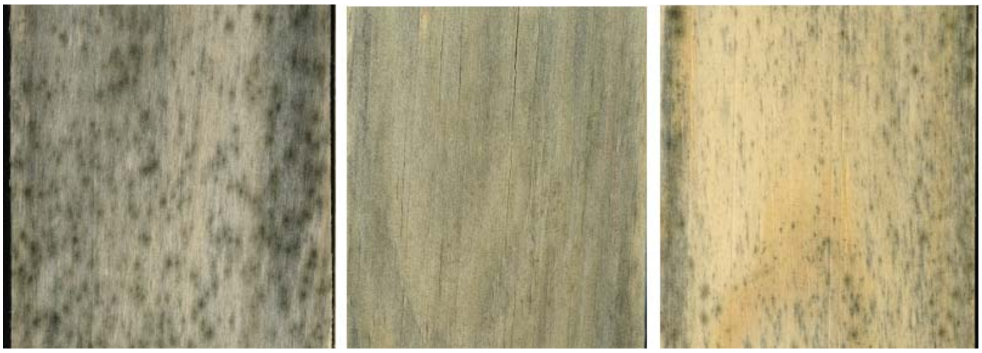

Figure 1. Surface mould growth on three different specimens of pine sapwood.

1.2 Factors affecting mould growth

Fungal growth can be divided into different phases as shown in Figure 2. The mould growth is affected by several factors. Physical and chemical factors are: Nutrients, water, air, temperature, pH value, light, and the force of gravity (Schmidt 2006). The conditions on the wood surface are decisive for the surface moulds. The mould hyphae only penetrate the wood a few millimetres and will use sugar, starch and protein as nutrients (Schmidt 2006).

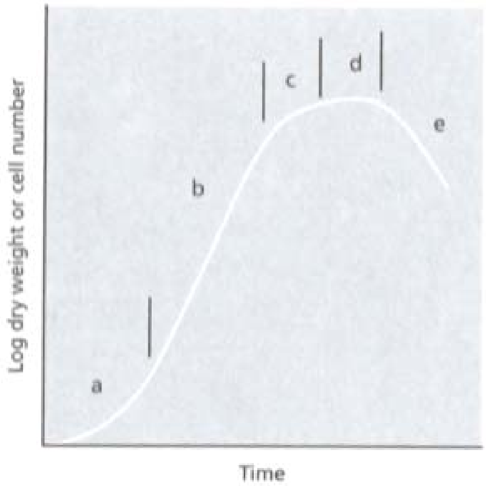

Figure 2. Typical growth of a batch culture: a: Lag phase, b: Exponential phase, c: Deceleration phase, d: Stationary phase; e: Phase of autolysis. Reproduced from Deacon (2006).

1.2.1 Temperature and moisture content

Different mould species have varying requirements and optimum for temperature and humidity. Generally, moulds are able to grow between 0 and 50 °C (Sedlbauer 2001), and the optimal temperature is between 20 and 35 °C for most species (Viitanen 1996). Moulds can survive periods in colder conditions, but very high temperatures can be lethal to the moulds (Mattsson 2004). The required humidity depends on temperature, exposure time and material quality (Viitanen et al. 2011). Moulds are able to survive dry conditions and continue to grow again when the humidity increases (Viitanen and Bjurmann 1995; Pasanen et al. 2000).

The moisture content is commonly considered as the most important factor affecting wood degradation by fungi (Ayerst 1969; Schmidt 2006; Sedlbauer 2001). Relative humidity is often used to describe the critical moisture conditions for initiation and development of mould growth. The required relative humidity for spore germination can be as low as 70 % under favourable temperatures (Figure 3), but for mould development the required humidity may be higher. Generally, humidity conditions corresponding to 80 % RH are considered as the critical limit for mould development (Adan 1994; Gobakken et al. 2010; Sedlbauer 2001; Viitanen et al. 2011). For sensitive materials the critical limit may be lower than 80 % RH. According to Johansson et al. (2012), critical moisture level that may lead to mould growth is expected between 75 – 80 % RH at 22 °C and between 85 – 90 % RH at 10 °C for pine sapwood. By calculating the equilibrium wood moisture content at a given RH (Forest Products Labaratory 2010), critical RH values derived from Johansson et al. (2012) gives the critical wood moisture content to be 18 - 21 % at 10 °C and 14 - 16 % at 22 °C.

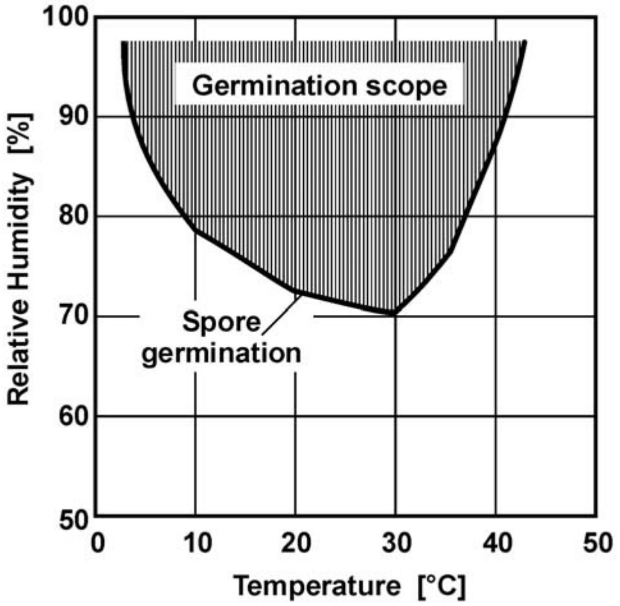

Figure 3. Required temperature and relative humidity for spore germination and mould growth. Reproduced from Sedlbauer (2001).

When periods of favourable conditions are interrupted by periods of less favourable conditions, the mould growth rate decreases. This also means that the mould can grow in dry conditions if sufficient moisture is supplied during given periods. Viitanen and Bjurman (1995) studied mould growth under fluctuating humidity conditions and found slower mould growth when periods of high humidity (97 - 100 % RH) were interrupted by periods of low humidity (75 % RH). Adan (1994) introduced the concept of time-of-wetness (TOW), describing the amount of time the relative humidity exceeded 80 % during one day, and found mould growth when the TOW was at least 4 hours per day. Sedlbauer (2001) stated that if high peaks of 95 % RH lasts more than 3 hours a day, rapid mould growth is expected.

More knowledge about the critical levels and interactions of the factors affecting mould growth is required to predict the mould growth more accurately on materials exposed outdoors. Most studies have examined mould growth in relation to indoor conditions (Adan 1994; Block 1953; Johansson 2012; Viitanen and Ritschoff 1991), and in such cases frequent wetting of the material was not investigated because it should not occur. Outdoors, wetting of a facade by liquid water can occur by wind driven rain, fog or condensation caused by a temperature drop, and this may greatly affect the development of surface mould growth. Fluctuations in temperature and humidity may be smaller indoors than outdoors, giving more stable moisture content in the materials indoors. Also, the average moisture content is usually lower in wood used indoors than outdoors. Wood can absorb moisture much faster from liquid water than from the humidity in the air (Forest Products Laboratory 2010), and therefore it is not enough to use the relative humidity of the air to describe the wood moisture content. By studying how the wood moisture affects the mould growth, more reliable models can be developed. This has been done for fungal decay of wood; dose-response models have been developed using the wood moisture content and temperature to predict the decay (Brischke and Rapp 2008). Thelandersson et al. (2009) proposed a dose-response model to predict the onset of mould growth, using relative humidity as the humidity factor. Since the model does not take liquid water into account, it cannot be applied to unsheltered materials exposed outdoors.

Periods where the wood surface is wetted by liquid water may greatly affect the mould growth, both by supplying moisture directly to the moulds, and by wetting the material and increasing the time of wetness. Viitanen and Ritschoff (1991) stated that the moisture content of the surrounding atmosphere may be more effective for the mould growth than the moisture content of the substrate, but below a RH of 97 to 100 % the moulds cannot obtain moisture directly from the atmosphere, and have to derive it from the substrate. Studies carried out in a laboratory indicate that wet conditions may lead to rapid mould growth (Viitanen 1996; Pasanen 2000), but the results may be different outdoors where heavy rain may even wash off the moulds. Gobakken et al. (2010) studied wooden claddings exposed outdoors and found a significant effect of relative humidity but not precipitation.

Periods with wetting of the wood surface may also change the way other factors affect the mould growth. The effect of relative humidity may be reinforced because the relative humidity also affects the drying rate and time of wetness. A small change in temperature can make a significant difference on the mould growth, and increased temperature may actually lower the mould growth. Gobakken et al. (2008) found less mould growth on the parts of a facade that were warmer because of thermal bridges. The difference in temperature shortened the time of wetness enough to make the warmer parts less susceptible to fungal growth.

1.2.2 Wood properties

The wood properties vary both between species and stem position, and small variations in wood properties can have large effects on the woods susceptibility to mould growth. Porosity, permeability and extractive composition of the wood are the most important factors for wood durability (Viitanen 1994). Wood is a hygroscopic material; the moisture content depends on the relative humidity of the ambient air. Block (1953) stated that a more hygroscopic material requires a lower relative humidity to support mould growth. The water permeability may however vary more between species and between heartwood and sapwood than the hygroscopicity. Viitanen and Ritschkoff (1991) studied mould growth on Scots pine and Norway spruce. They found a difference in water permeability but not hygroscopicity between the materials, and this caused heavier mould growth on pine sapwood than spruce sapwood. Pine has larger pores than spruce, allowing the water to flow more easily between the cells (Weider and Skogstad 1999), and the water permeability seems to be especially low for spruce with small annual growth rings (Flæte and Alfredsen 2004). In several species, the heartwood contains extractives that are toxic to the fungi, making heartwood generally more durable than sapwood (Zabel and Morell 1992, Eaton and Hale 1993). Pine heartwood is less permeable than pine sapwood and contains extractives (Øvrum and Flæte 2008). Pine sapwood also has a relatively high content of compounds that can be used as nutrients by the moulds (Skaug 2007). Aspen is a very permeable material and can therefore quickly absorb moisture (Michalec and Niklasová 2006; Flæte and Eikenes 2000). This may lead to rapid mould growth. However, most laboratory experiments on mould growth on wood are done with pine and spruce, and less is known about the mould growth on aspen. Hence, the critical limits for mould growth on aspen may differ from the critical limits derived from studies on spruce and pine.

The effects of wood properties may be especially large under fluctuating conditions. Blom et al. (2013) studied susceptibility to mould growth and water uptake of Scots pine and Norway spruce. The wood was subjected to cycles of 100% RH, followed by dry periods of about 50% RH, and results after 12 weeks showed that sapwood was more susceptible to mould growth than heartwood for both Scots pine and Norway spruce. The test of water uptake showed that pine heartwood had lower water uptake than pine sapwood, but there were also significantly higher density and smaller annual ring width for the heartwood, making it hard to determine which property was most important. The water uptake was also lower in spruce heartwood than spruce sapwood, but not the calculated moisture content, presumably because of the difference in density.

Wood with high density is often considered as more durable than wood with lower density within the same species, but this has been questioned in several studies (Flæte and Høibø 1999). Brishke et al. (2006) stated that wood species with high density are not necessarily more resistant to fungi. Sivertsen and Vestøl (2010) found a lower void filling rate with increasing heartwood proportion in Norway spruce, and the heartwood proportion was more important than the density regarding the effects of capillary uptake.

1.3 Aim of thesis

Increased knowledge about factors affecting surface mould growth may increase the use of untreated wood as a cladding material by making the weathering of a building facade easier to predict. Several previous studies have investigated factors affecting mould growth in relation to indoor conditions, but less is known about the factors affecting mould growth on untreated wood exposed outdoors. Wooden facades may be periodically subjected to liquid water and this can both affect the mould growth directly and alter the way other factors affect the mould growth.

The aim of this study was to investigate the development of surface mould growth and moisture content on untreated wood of aspen, Norway spruce and Scots pine exposed to different temperature, relative humidity and wetting periods. Wood properties that were investigated are heartwood/sapwood and density.

2 Materials and methods

2.1 The wood material

2.1.1 Wood species

Three wood species were included in this study:

- Aspen (*Populus tremula* (L.))
- Scots pine (*Pinus sylvestris* (L.))
- Norway spruce (*Picea abies* (L.) Karst)

The aspen material and Scots pine material were collected at Svenneby, a sawmill in Spydeberg, Norway. There was no information about the origin of this material. The Norway spruce material was collected from two sites in Hobøl, Norway; one 160 years old stand with site index G17 and one 45 years old stand with site index G26. The material from G17 was known to have high density, and due to a larger annual ring width, the material from G26 was assumed to have lower density (Høibø et al. 2014). Five trees were sampled from each stand, and the heartwood was detected using infrared camera and marked on the end of the logs. After sawing and kiln drying, the boards were adjusted to 19 mm thickness, and boards with a dry sawn surface towards the pith were used in the experiment. Due to narrow sapwood it was only possible to use boards with heartwood from the G17 stand, but from the G26 stand one board of sapwood and one board with heartwood were sampled from each tree and used in the study

2.1.2 Preparation of specimens

In total, 240 specimens were used in this study. The specimens were evenly distributed between the eight climatic chambers, depending on species and eventual sapwood/heartwood and site index (Table 1). There were initially five boards of each wood type (combination of species and eventual sapwood/heartwood and site index) presented in Table 1. Each board was cut into eight parts, providing one specimen of each board for each climatic chamber. The material was conditioned at 65 % RH and 20 °C. The spruce sampling made it possible to compare the effect of heartwood and sapwood on the wood from G26, and the effect of density on the heartwood specimens from G17 and G26.

Table 1. Specimens in each of the eight climatic chambers.

Material	Species	Sapwood/heartwood	Site index	N
1	Aspen	-	-	5
2	Scots pine	Heartwood	-	5
3	Scots pine	Sapwood	-	5
4	Norway spruce	Heartwood	G17	5
5	Norway spruce	Heartwood	G26	5
6	Norway spruce	Sapwood	G26	5

After the boards were cut into eight parts, the dimensions of the wooden specimens were initially 18 x 50 x 250 mm. The specimens were cut down to 18 x 50 x 200 mm (Figure 4), and weighed, before the end grain faces were sealed with three layers of End Grain Sealer, and a screw was attached on the back of each specimen. The specimens were weighed again, and stored at 65 % RH and 20 °C until they were placed in the climatic chambers. The 50 mm remaining pieces were trimmed to get a knot-free test piece with approximate dimensions 18 x 50 x 30 mm to measure initial moisture content and density (Figure 4). This moisture content was used as an estimate of the 200 mm samples at the beginning of the experiment.

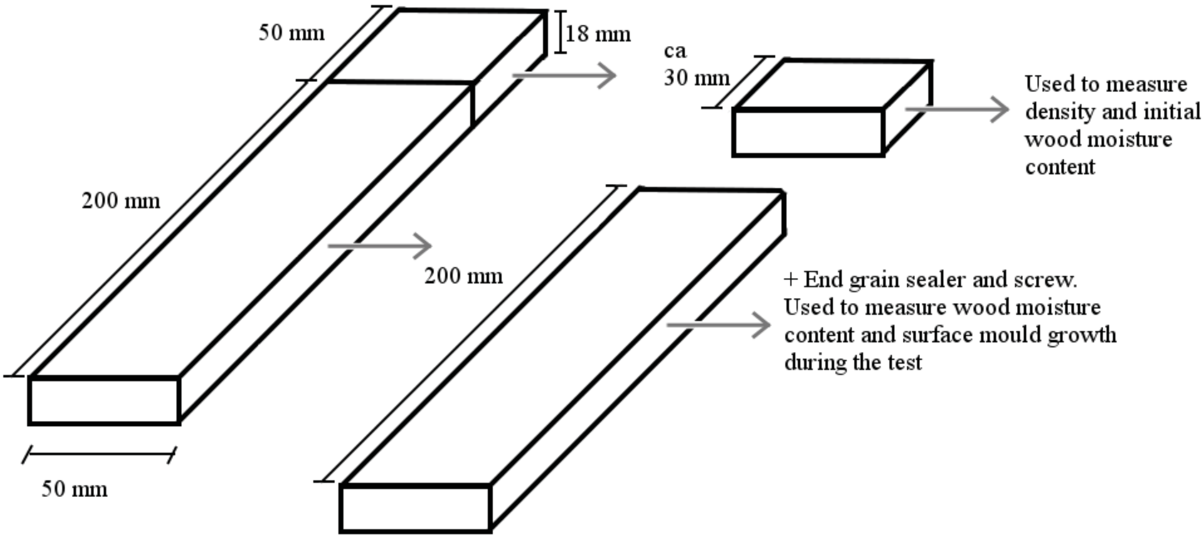

Figure 4. Division of the specimens.

Determination of initial moisture content

Initial moisture content was determined from the 18 x 50 x 30 pieces in accordance to SKANORM (1992). The 18 x 50 x 30 mm pieces were first weighed and then dried at 103 °C until the mass was constant. After being cooled in desiccator, the pieces were weighed again.

The moisture content was calculated using equation 1, and is expressed in percentage with an accuracy of 0,1 %.

$$w_{\%} = \frac{m_w - m_0}{m_0} \times 100 \qquad (1)$$

Where

$w_{\%}$ = The moisture content of the piece given in percentage of dry weight

m_w = The mass of the test piece before drying

m_0 = The mass of the test piece after drying.

Determination of density

Density was determined from the 18 x 50 x 30 mm pieces in accordance to SKANORM (1992). The pieces were weighed and dipped in water, measuring mass and volume. The density was calculated using equation 2.

$$\rho_w = \frac{m_w}{V_w} \qquad (2)$$

Where

ρ_w = The density of the test piece by the moisture content (w) the piece had at the testing time

m_w = The mass of the test piece by the moisture content (w) the piece had at the testing time

V_w = The volume of the test piece by the moisture content (w) the piece had at the testing time.

Adjustment of density

The density of the test pieces was adjusted to 12 % moisture content in accordance to SKANORM (1992), using equation 3. The results are expressed in kg/m^3 with an accuracy of 5 kg/m^3.

$$\rho_{12} = \rho_w \times \left(1 - \frac{(1-K)\times(w-12)}{100}\right) \qquad (3)$$

Where

ρ_{12} = The adjusted density of the test piece

ρ_w = The density of the test piece by the moisture content (w) the piece had at the testing time, calculated by equation 2.

K = Coefficient for volume shrinkage at a 1 % change in moisture content = 0.5.

Mean values of initial moisture content and density of the specimens

Mean values of density and the initial moisture content of the wood material are presented in Table 2. The specimens of Norway spruce with site index G26 had generally lower density than the specimens of Norway spruce with site index G17.

Table 2. Initial moisture content and density of the specimens. There were 40 specimens of each wood type.

			Moisture content (%)		Density (kg/m^3)	
Species	Sap/heart	Site index	Mean	SD	Mean	SD
Aspen	-	-	10.5	0.3	510	55
Scots pine	Heartwood	-	13.4	0.4	515	50
Scots pine	Sapwood	-	11.0	0.6	580	40
Norway spruce	Heartwood	G17	14.0	0.4	505	25
Norway spruce	Heartwood	G26	13.2	0.6	400	50
Norway spruce	Sapwood	G26	13.8	0.5	415	45

Determination of the dry matter content of the 18 x 50 x 200 mm specimens

It was assumed that the 18 x 50 x 200 mm specimens had the same initial moisture content as the 18 x 50 x 30 mm pieces. By calculating the dry matter of the specimens, the moisture content during the exposure period could be calculated by weighing the specimens. The dry matter content of each specimen was calculated using equation 4.

$$m_{dry} = \frac{m_w}{1 + \frac{w_{\%}}{100}} \tag{4}$$

Where

m_{dry} = The mass of the dry matter content of the specimen.

$w_{\%}$ = The moisture content of the 18 x 50 x 30 mm piece, calculated by equation 1.

m_w = The mass of the 18 x 50 x 200 mm specimens during storage at 65 % RH and 20 °C.

2.2 Climatic chambers and growth conditions

The climatic chambers were 7.85 m^3 with the dimension 1.95 x 2.30 x 1.75 m (length x height x width). A sluice room for entering separated the chambers from the external environment. The climate-controlled parameters were air humidity, temperature and lighting. The parameters were managed and controlled via a Priva system, and were carried out by cooling and heating batteries and electrical circuits. For lightning, incandescent bulbs were used. During one day, the bulbs were 12 hours on and 12 hours off.

A rig was installed in each chamber (Figure 5). On one side of the rig, there were two racks covered with plastic mesh for mounting the specimens, and a water hose with five nozzles for water spraying was attached to the other side of the rig. The specimens were distributed randomly on the racks and the order of the specimens was rotated each week during the exposure period to eliminate any effect of position relative to the nozzles.

Figure 5. Test rig with specimens. As this experiment was a part of a larger project, there were more specimens on the rig than what was studied in this thesis.

The water nozzles were, relatively to each other, placed close enough to cause an overlap that made each specimen receive an even water spray from two nozzles (Figure 6). The water spray was very light, almost like a water mist, to try to mimic wetting of wood occurring by condensation and to ensure the water being evenly distributed on the front face of the specimens.

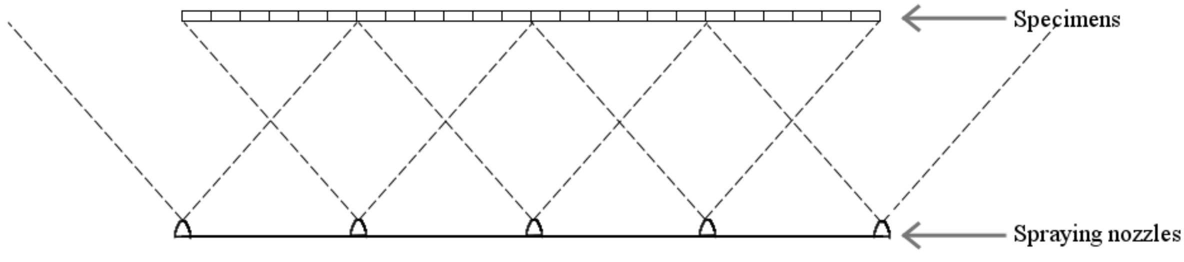

Figure 6. Illustration of the water spraying from the nozzles, as seen from above.

Three climatic factors with two levels of each factor (complete block design) were included in the experiment. The factors and levels were:

- Temperature: 10 and 25 °C.
- Relative humidity: 65 and 85 %.
- Wetting period: 2 and 4 hours.

In total, eight climatic chambers were included in this study and the settings and length of exposure period of each *climate* are presented in Table 3. *Climate* is in this thesis used as a term for the climatic chambers. Wetting period is meant to describe the water spraying. Water spray from the nozzles started at 17:00 each day during the exposure period, and gave one minute of water spray per 30 minutes in the wetting period. It is assumed that the front faces of the specimens were wet the entire wetting period. 2 hours wetting period gave 4 x 1 minute of water spraying. 4 hours wetting period gave 8 x 1 minute of water spraying.

Table 3. Temperature, moisture settings and length of exposure period in the eight different *climates*.

Climate	Temperature (°C)	Relative humidity (%)	Wetting period (hours)	Exposure period (days)
1	25	85	2	91
2	10	85	2	91
3	25	65	2	119
4	10	65	2	119
5	25	85	4	91
6	10	85	4	91
7	25	65	4	119
8	10	65	4	119

Before, during and after the exposure period, several activities were performed in the climatic chambers (Figure 7). The specimens were mounted on the rigs in the climatic chambers to get acclimatised for eleven days before the exposure period started. There was no water spraying during the acclimatisation period, and this period is further described in section 2.2.2 (Acclimatisation period). Day 0 of the exposure period is defined as the day the spore suspension was applied to the specimens. The spore suspension and application is described in 2.3 (Fungi). The water spraying started the day after the spore suspension was applied to the specimens and this is referred to as day 1 of the exposure period.

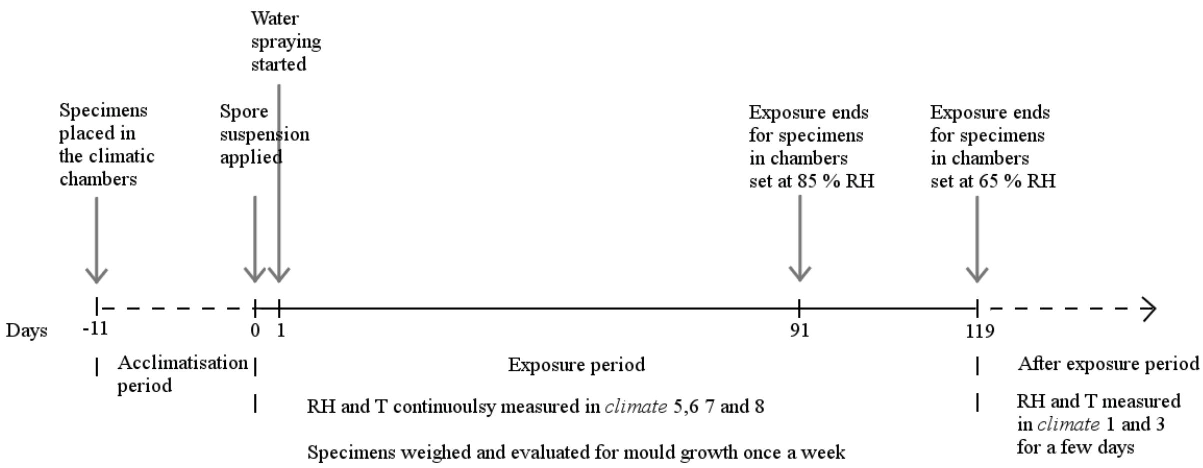

Figure 7. Activities in the climatic chambers.

2.2.1 Measured relative humidity and temperature in the climatic chambers

During the exposure period, relative humidity and temperature of the air were measured in the chambers with 4-hours wetting period (*climate* 5 - 8). The means of measured temperature in *climate* 5 - 8 were nearly identical to the set values, with low standard deviation, but the means of measured RH showed larger deviations from the set value (Table 4). *Climate* 5 had quite stable RH around the set value during the exposure period and low standard deviation. *Climate* 6 and 7 had mean measured RH close to the set value but some larger standard deviation. In *climate* 6, the measured RH was slightly higher than the set value during the first month, and the measured RH stabilized around the set value after this. Means of measured RH in *climate* 8 were about 5 % higher than the set value, and had quite large standard deviation. Deviations from the set RH occurred both the first month and the last month of the exposure period in *climate* 8.

Table 4. Measured relative humidity and temperature in *climate* 5 - 8.

	RH (%)		T (°C)	
Climate	Mean	SD	Mean	SD
5	84.8	1.2	25.0	0.2
6	86.7	2.8	10.0	0.3
7	65.6	3.4	25.2	0.3
8	70.2	6.2	10.1	0.4

Note: Mean values for exposure period (91 days for *climate* 5 and 6, 119 days for *climate* 7 and 8). Measurements were recorded with 5-minute intervals.

After the exposure period was finished, deviations from the set values were suspected in two of the other chambers (*climate* 1 and 3). Therefore, an additional measurement of relative humidity and temperature was conducted in these two climatic chambers. This was a short test (lasting two days), and there was no water spraying during these additional measurements since the measurements were conducted after the exposure period was finished. Means of measured RH in *climate* 1 and 3 were about 5 % lower than the set values, and the means of measured temperature were almost 1 °C higher than the set value (Table 5). The standard deviations of these measurements were low.

Table 5. Measured relative humidity and temperature in *climate* 1 and 3.

	RH (%)		T (°C)	
Climate	Mean	SD	Mean	SD
1	79.5	1.0	25.8	0.4
3	58.1	1.0	25.7	0.3

Note: Mean values for 2 days, measured after the experiment was finished (without water spraying in the chambers). Measurements were recorded with 5-minute intervals.

2.2.2 Acclimatisation period

The specimens had an acclimatisation period lasting 11 days in the climatic chambers before the exposure period started. The relative humidity and temperature were set at the same values as during the exposure period, but there was no water spraying in the chambers during the acclimatisation period. The specimens were weighed after 7 and 11 days to make sure the specimens were acclimatised before the spore suspension was applied.

The mean calculated MC of all specimens in each *climate* during the acclimatisation period is presented in figure 8. The MC was calculated using equation 5.

$$w_{\%} = \frac{m_{w-ss} - m_{dry}}{m_{dry}} \times 100 \qquad (5)$$

Where

$w_{\%}$ = The moisture content of the specimen given in percentage

m_{w-ss} = The weighed mass of the specimen minus the mass of end gran sealer and screw

m_{dry} = The dry matter content of the specimen, calculated by equation 4.

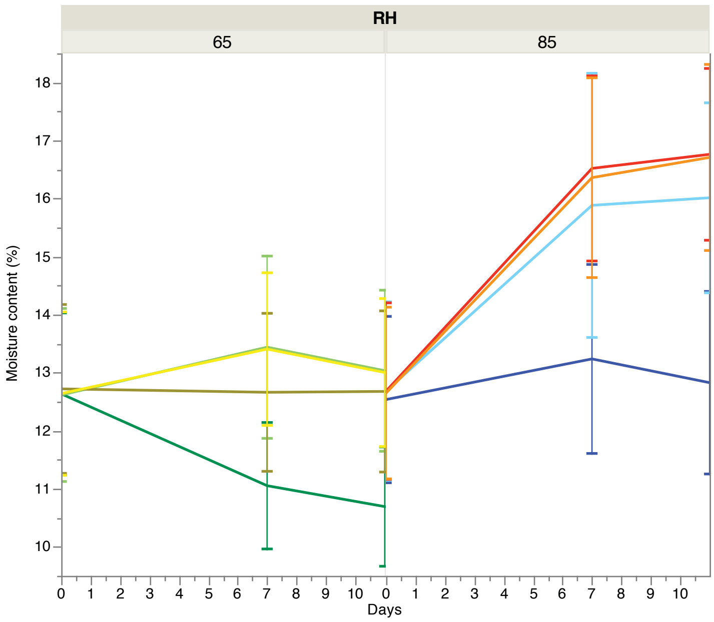

Figure 8. Wood moisture content during the acclimatisation period. Values for day 0 are MC during storage at 20 °C and 65 % RH. Lines show mean values of all specimens in each *climate* and error bars show standard deviation.
Climate:
1: 25 °C, 85 % RH, 2h wetting period
2: 10 °C, 85 % RH, 2h wetting period
3: 25 °C, 65 % RH, 2h wetting period
4: 10 °C, 65 % RH, 2h wetting period
5: 25 °C, 85 % RH, 4h wetting period
6: 10 °C, 85 % RH, 4h wetting period
7: 25 °C, 65 % RH, 4h wetting period
8: 10 °C, 65 % RH, 4h wetting period

There was some unexpected variation in MC between the *climates* after the acclimatisation period. Since the water spraying had not started, the MC of the specimens was expected to be equal in the corresponding *climates* with same temperature and RH but different wetting period (i.e. *climate* 1 and 5, 2 and 6, 3 and 7, 4 and 8). Specimens in *climate* 1 and 3 had lower MC than in the other corresponding *climates*. The same tendency applied to all species.

2.3 Fungi

The spore suspension contained three test fungi: *Ulocladium atrum* 06/55, *Cladosporium cladosporioides* 06/54 and *Aureobasidium pullulans* BAM 9. According to NS-EN 15457 (Standard Norge 2014), these fungi are likely to grow in an exterior environment. The spore suspension was made using well sporulating cultures on agar dishes. 38 dishes from each of the test fungi were used. 5 ml sterile water was added to each agar dish. A bacteria loop was used to loosen the spores from the mycelium/agar. An equal amount of suspension from the 3 test fungi was mixed into a batch, giving in total 450 ml suspension. 5 - 7 drops of Tween80 were added to the suspension to make it more viscous. The suspension was divided into two bottles, 225 ml on each, and each bottle was filled up to 1000 ml with sterile water.

Before application of the spore suspension, the specimens were wetted by spraying water on them four times with a half-hour interval. The application of the spore suspension started one hour after the last water spray. The suspension was sprayed on the specimens using an air compressor. In total, approximately 330 - 400 ml of the spore suspension was applied to the 240 specimens.

2.4 Determination of wood moisture content and mould growth

During the exposure period, the moisture content of the specimens was calculated by weighing once a week. The weighing was done between 12:00 - 14:00, starting in the chambers with 2 hours wetting period. The moisture content was calculated using equation 5 (equation 5 was presented in section 2.2.2).

During the exposure period, mould growth was determined visually once a week (at the same time as the specimens were weighed). To minimize errors caused by subjective evaluations, two persons in collaboration made the evaluations. The mould rating was evaluated according to NS-EN 15457 (Standard Norge 2014). The rating ranged from 0 - 4 and the percentage area of disfigurements for each rating level is presented in Table 6. A hand held magnifying lens (x10 magnification) was used when contamination of dirt was suspected. Images of the specimens were also taken every week with a scanner for later double-checking the registered mould rating.

Table 6. Rating scheme for determination of mould growth, from NS-EN 15457 (Standard Norge 2014).

Rating	Percentage area of disfigurements
0	No growth on the surface of the specimen
1	Up to 10 % growth on the surface of the specimen
2	More than 10 % up to 30 % growth on the surface of the specimen
3	More than 30 % up to 50 % growth on the surface of the specimen
4	More than 50 % up to 100 % growth on the surface of the specimen

2.5 Statistical analysis

Ordinal logistic regression was used to analyse how the different factors affected the mould rating. Logistic regression models the probability of the occurrence of the different mould ratings using different explanatory variables. *Mould rating* (0 - 4) was used as categorical (ordinal) response variable in all the analyses. *RH* (65 % / 85 %), *T* (10 °C / 25 °C), *wetting* *period* (2 hours / 4 hours), w*ood material* (aspen / pine heartwood / pine sapwood / spruce heartwood / spruce sapwood) and *quality* (heartwood / sapwood) were classified as categorical explanatory variables. *Time* (number of days) and *MC between day 35 - 84* (%) were classified as continuous explanatory variables. The data were weighed down to get the degrees of freedom in accordance with the number of specimens (specimens in *climates* at 85 % RH: Weight = 1/14 = 0,0714, specimens in *climates* at 65 % RH: Weight = 1/18 =0,0556).

To investigate the effect of different factors, the statistical analysis was divided into five steps. *RH*, *T*, *wetting period* and *time* were included as explanatory variables in all the tested models in step 1, 3, 4 and 5. Interactions of the variables were also tested in all models in step 1, 3, 4 and 5. The R^2, RMSE and Misclassification rate were used to find the best fit of the models containing only significant variables. Significance level was set to $p < 0.05$.

The 1st step's purpose was to test the significance of wood material. Data of all species were included to model mould rating, using *wood material* addition to *RH*, *wetting period*, *T* and *time* as explanatory variables.

The 2nd step's purpose was to test the significance of the wood moisture content during the exposure period. Data of all species were included in the model and *MC between day 35 - 84* for each specimen was used together with *time* as explanatory variables. *MC between day 35 – 84* is the mean of the calculated wood moisture content between day 35 - 84 of the exposure period.

The 3rd step's purpose was to test the significance of relative humidity, wetting period temperature, time and density for each wood material. Mould rating was modelled separately for all wood materials, using *density* in addition to *RH*, *wetting period*, *T* and *time* as explanatory variables.

The 4th step's purpose was to test the significance of heartwood and sapwood. Mould rating was modelled separately for pine and spruce, including *quality* in addition to *RH*, *wetting period*, *T* and *time* as explanatory variables. Only spruce specimens from G26 were included to exclude any confounding effect of density.

The 5th step’s purpose was to examine whether deviations from the settings in the climatic chambers affected the results from the statistical analyses or not. Step 1, 3 and 4 were performed an additional time without including data from *climate* 1, 3 and 8 (Measured RH deviated about 5 % from the settings in these *climates*, see Table 4 and 5). Since both *climate* 1 and *climate* 3 were set at 25 °C and 2 hours wetting period, the interaction effect of *T* and *wetting period* could not be tested in this step.

The statistical analyses were performed with JMP®, version 11.0 (SAS Institute Inc. 2014). The sum of the parameters of a categorical explanatory variable is zero in logistic regression performed by JMP, and empty spaces may appear because one parameter is not tested against zero and therefore not listed in the test report.

3 Results

3.1 Surface mould growth and wood moisture content

3.1.1 Mould growth after 91 days

Means of the evaluations after 91 days of exposure (Figure 9) shows that aspen and pine sapwood had generally highest mould rating, and pine heartwood and spruce heartwood had generally lowest mould rating. Overall, higher mould rating was recorded in *climate* 5 and 6, and lower mould rating was recorded in *climate* 3 and 4.

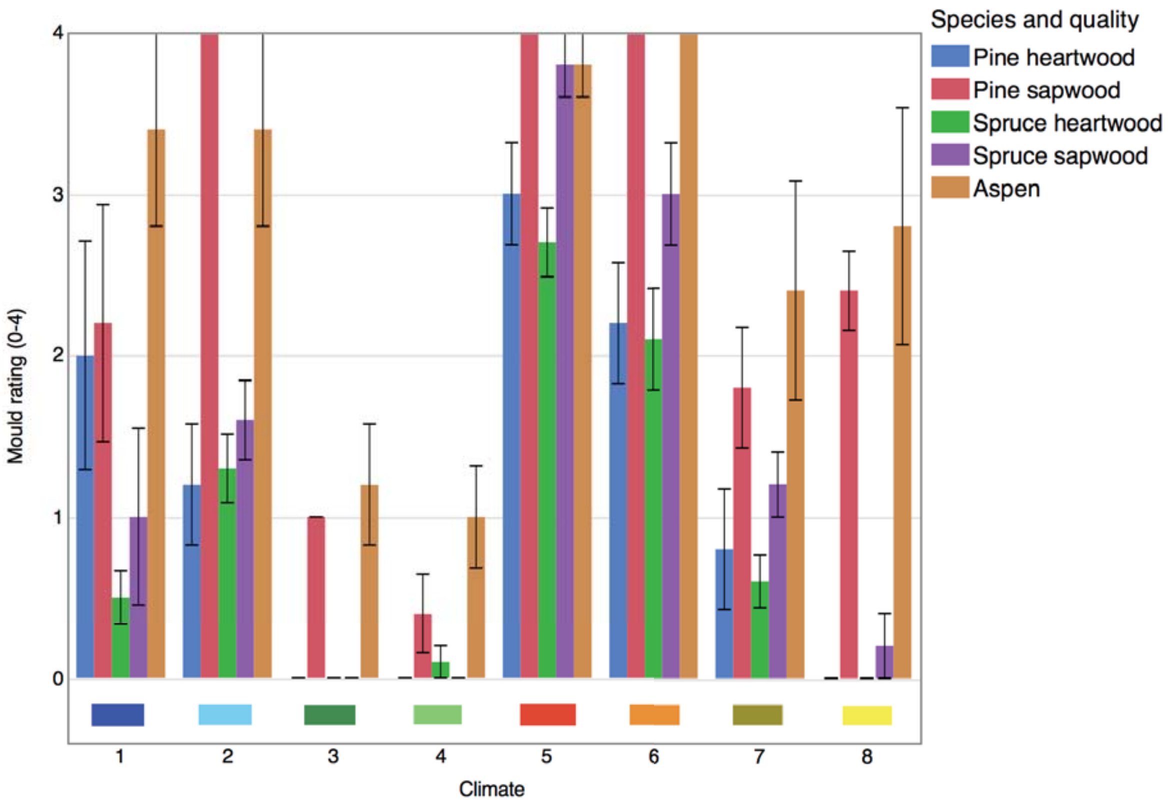

Figure 9. Mean mould ratings after 91 days exposure.
Climate:
1: 25 °C, 85 % RH, 2h wetting period
2: 10 °C, 85 % RH, 2h wetting period
3: 25 °C, 65 % RH, 2h wetting period
4: 10 °C, 65 % RH, 2h wetting period
5: 25 °C, 85 % RH, 4h wetting period
6: 10 °C, 85 % RH, 4h wetting period
7: 25 °C, 65 % RH, 4h wetting period
8: 10 °C, 65 % RH, 4h wetting period

The figures displaying mould rating (Figure 9 and Figure 12 - 15) shows mean response values and standard deviations. To clearly illustrate the results, the figures were made using mould rating as a continuous variable, even though it was treated as an ordinal variable in the statistical analyses.

3.1.2 Statistical analysis of mould growth on all species

Wood material, relative humidity, wetting period, temperature and exposure time significantly affected the development of surface mould growth when data of all species were analysed in one model (Table 7). There was also a significant interaction effect between temperature and wetting period. The model presented in Table 7 got a R^2 of 0.44, RMSE of 0.48 and Misclassification rate of 0.28.

Table 7. Test statistics for the factors included in the model based on data of all species (step 1).

Source	DF	L-R ChiSquare	p-value
wood material	4	115.72	<.0001
RH	1	134.26	<.0001
wetting period	1	61.64	<.0001
T	1	6.49	0.0109
time	1	110.81	<.0001
*T*wetting period*	1	9.18	0.0025

The parameter estimates for the significant factors are presented in Table 8. A positive parameter estimate indicates low mould rating and a negative parameter estimate indicate high mould rating. A larger number indicates larger impact on the mould rating. The parameter estimates indicate that aspen and pine sapwood were most susceptible to mould growth, and spruce heartwood and pine heartwood were least susceptible to mould growth. Aspen had a slightly lower parameter estimate than pine sapwood, and spruce heartwood had a slightly higher parameter estimate than pine heartwood. The parameter estimates also shows that increased relative humidity, wetting period and exposure time increased the mould rating. The parameter estimate of the interaction term indicates that the effect of wetting period was larger at higher temperature, and that the effect of temperature was different at different levels of wetting period; increased temperature had a positive effect on the mould rating in the *climates* with 4 hours wetting period, and a negative effect on the mould rating in the *climates* with 2 hours wetting period.

Table 8. Parameter estimates for the factors included in the model presented in table 7.

Term	Estimate	Std Error	ChiSquare	p-value
Intercept[0]	7.38	0.85	74.76	<.0001
Intercept[1]	9.60	0.99	93.44	<.0001
Intercept[2]	10.96	1.08	102.94	<.0001
Intercept[3]	11.83	1.13	109.11	<.0001
wood material[aspen]	-2.76	-	-	-
wood material[pine heartwood]	1.68	0.40	17.95	<.0001
wood material[pine sapwood]	-2.08	0.35	34.50	<.0001
wood material[spruce heartwood]	2.15	0.34	38.88	<.0001
wood material[spruce sapwood]	1.01	0.36	7.67	0.0056
RH[85-65]	-4.94	0.55	81.51	<.0001
wetting period[4-2]	-1.86	0.48	14.99	<.0001
T[25-10]	1.35	0.53	6.44	0.0111
time	-0.07	0.01	74.34	<.0001
T[25-10]* *wetting period*[4-2]	-2.05	0.69	8.88	0.0029

When the statistical analyses were performed excluding *climate* 1, 3 and 8 (step 5), the only considerable difference from the results presented above was that the effect of temperature was no longer significant (p = 0.2062). The interaction between temperature and wetting period could not be tested when these *climates* were removed from the data.

The test statistics (Table 7 and 8) shows that there were differences between wood materials regarding the development of mould rating. The mould growth is therefore further presented for each wood material in section 3.2.

3.1.3 Wood moisture content during the exposure period

Mean calculated wood moisture content of all specimens in each *climate* is presented in Figure 10. In *climate* 2, 6 and 8, the wood moisture content seemed to reach a peak after 21 days, and then decrease before it stabilized. The most stable period seemed to be between 35 and 84 days, therefore mean moisture content between these days was calculated for the specimens to try to find a representative value for the wood moisture content during the exposure period (Figure 11).

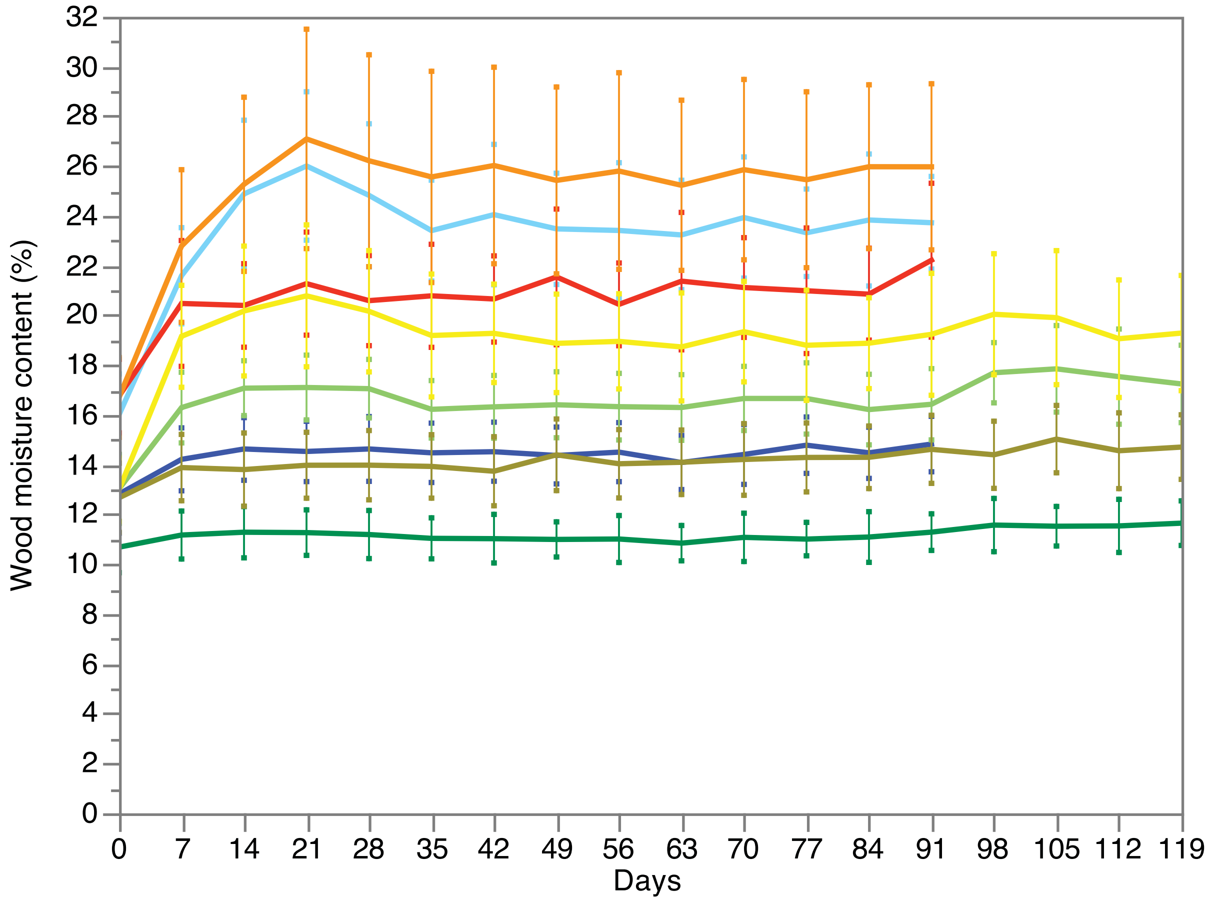

Figure 10. Wood moisture content during the exposure period. Lines show mean values of all specimens in each *climate* and error bars show standard deviation.

Climate:

- 1: 25 °C, 85 % RH, 2h wetting period
- 2: 10 °C, 85 % RH, 2h wetting period
- 3: 25 °C, 65 % RH, 2h wetting period
- 4: 10 °C, 65 % RH, 2h wetting period
- 5: 25 °C, 85 % RH, 4h wetting period
- 6: 10 °C, 85 % RH, 4h wetting period
- 7: 25 °C, 65 % RH, 4h wetting period
- 8: 10 °C, 65 % RH, 4h wetting period

The specimens in *climate* 1 and 3 had lower mean MC during the exposure period (Figure 10) than the specimens in *climates* with corresponding settings had during the acclimatisation period (Figure 8). During the exposure period, the MC was below 15 % and 12 % for all species in climate 1 and 3. After the acclimatisation period, the other *climates* with 85 % RH (*climate* 2, 5 and 6) had MC around 16 %, and the other climates with 65 % RH (*climate* 4, 7 and 8) had MC around 13 %.

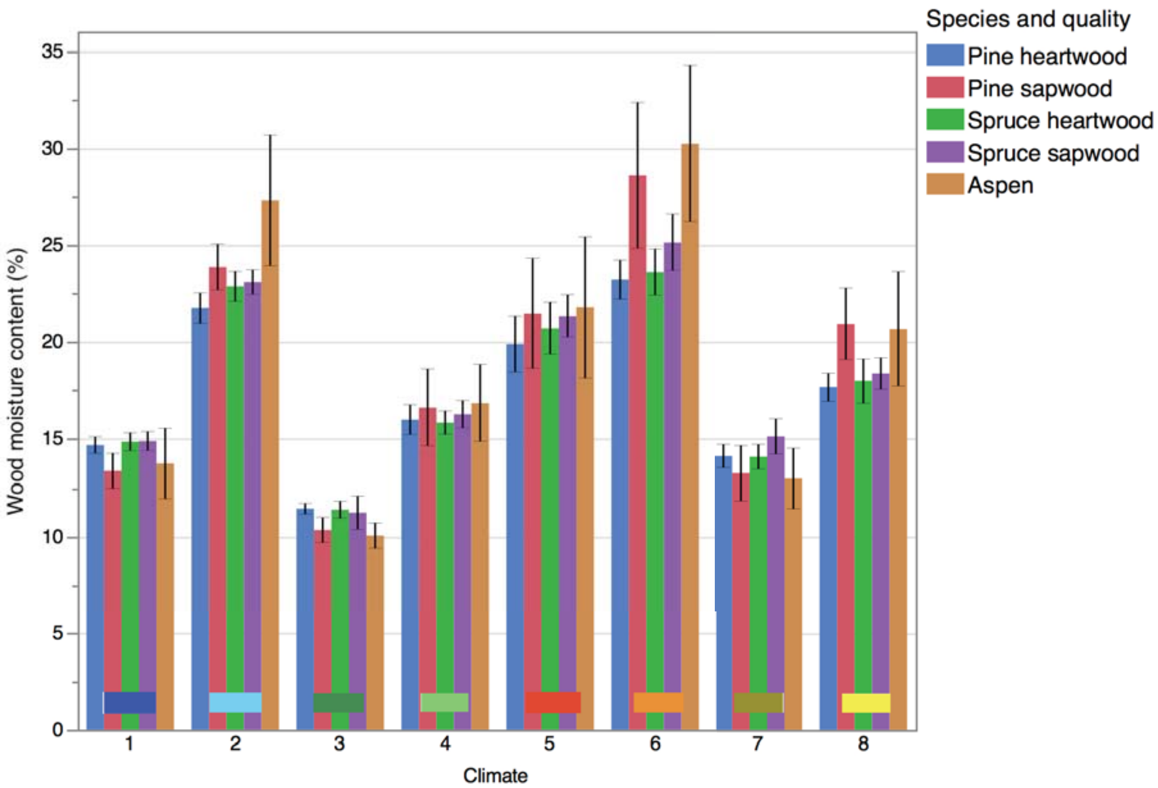

Figure 11. Mean wood moisture content between day 35-84. Error bars show standard deviation. Only spruce specimens from site index G26 are included.
Climate:

1: 25 °C, 85 % RH, 2h wetting period	5: 25 °C, 85 % RH, 4h wetting period
2: 10 °C, 85 % RH, 2h wetting period	6: 10 °C, 85 % RH, 4h wetting period
3: 25 °C, 65 % RH, 2h wetting period	7: 25 °C, 65 % RH, 4h wetting period
4: 10 °C, 65 % RH, 2h wetting period	8: 10 °C, 65 % RH, 4h wetting period

The mean wood moisture content varied between *climates* and between wood materials (Figure 11). The variation between wood materials seemed to be largest in *climate* 2 and 6. These *climates* were also the *climates* with the overall highest mean moisture content. Aspen and pine sapwood had higher MC than the other wood materials in *climate* 2, 4, 5, 6 and 8, where all materials had MC higher than 15 %. In *climate* 1, 3 and 7, all wood materials had MC around 15 % or below, and aspen and pine sapwood had lower MC than the other materials. Similar results occurred for spruce sapwood and spruce heartwood, with slightly higher MC for spruce sapwood in *climates* with MC higher than 15 %.

The lowest mean MC for reaching mean mould rating 1 within 91 days varied between wood materials (Figure 11 compared with Figure 9): For aspen it was 10.0 %, and this occurred in *climate* 3. For pine heartwood it was 14.7 % (*climate* 1) and for pine sapwood it was 10.3 % (*climate* 3). For spruce heartwood it was 20.7 % (*climate* 5) and for spruce sapwood it was 14.9 % (*climate* 1).

3.1.4 Statistical analysis of wood moisture content and mould rating

Mean moisture content between day 35-84 and exposure time had a significant effect on the development of mould rating (Table 9). The model presented in Table 9 got a R^2 of 0.19, RMSE of 0.58 and Misclassification rate of 0.38. The parameter estimates indicated that the mould rating increased with increasing moisture content and increasing exposure time (Table 10).

Table 9. Test statistic for the model using moisture content and exposure time as explanatory variables (step 2). Data of all species are included.

Source	DF	L-R ChiSquare	p-value
MC between day 35-84	1	80.81	<.0001
time	1	55.71	<.0001

Table 10. Parameter estimates for the factors included in the model presented in table 9.

Term	Estimate	Std Error	ChiSquare	p-value
Intercept[0]	7.34	0.85	75.22	<.0001
Intercept[1]	8.61	0.90	90.88	<.0001
Intercept[2]	9.38	0.94	100.06	<.0001
Intercept[3]	9.89	0.96	105.88	<.0001
MC between day 35-84	-0.27	0.03	63.57	<.0001
time	-0.03	0.005	46.80	<.0001

3.2 Development of surface mould growth on each wood material

3.2.1 Aspen

Compared to the other species, mould growth on aspen began rapidly and reached high mould rating. Mould rating on aspen during the exposure period is presented in Figure 12. Mean mould rating 1 occurred within one week in *climate* 5, and after 91 days, all *climates* had mean mould rating 1 or higher. Relative humidity and wetting period had significant effects on the mould rating on aspen (Table 11). Figure 12 shows that increased relative humidity and increased wetting period had a positive effect on the mould growth. The growth initiated earlier and reached higher rating in *climates* with 85 % RH (*climate* 1, 2, 5 and 6) than in *climates* with 65 % RH (*climate* 3, 4, 7 and 8). Of the *climates* with 85 % RH, the *climates* with 4 hours wetting period (*climate* 5 and 6) reached higher mould rating than the *climates* with 2 hour wetting period (*climate* 1 and 3). This also applied to the *climates* with 65 % RH; *climate* 7 and 8 reached higher mould rating than *climate* 3 and 4.

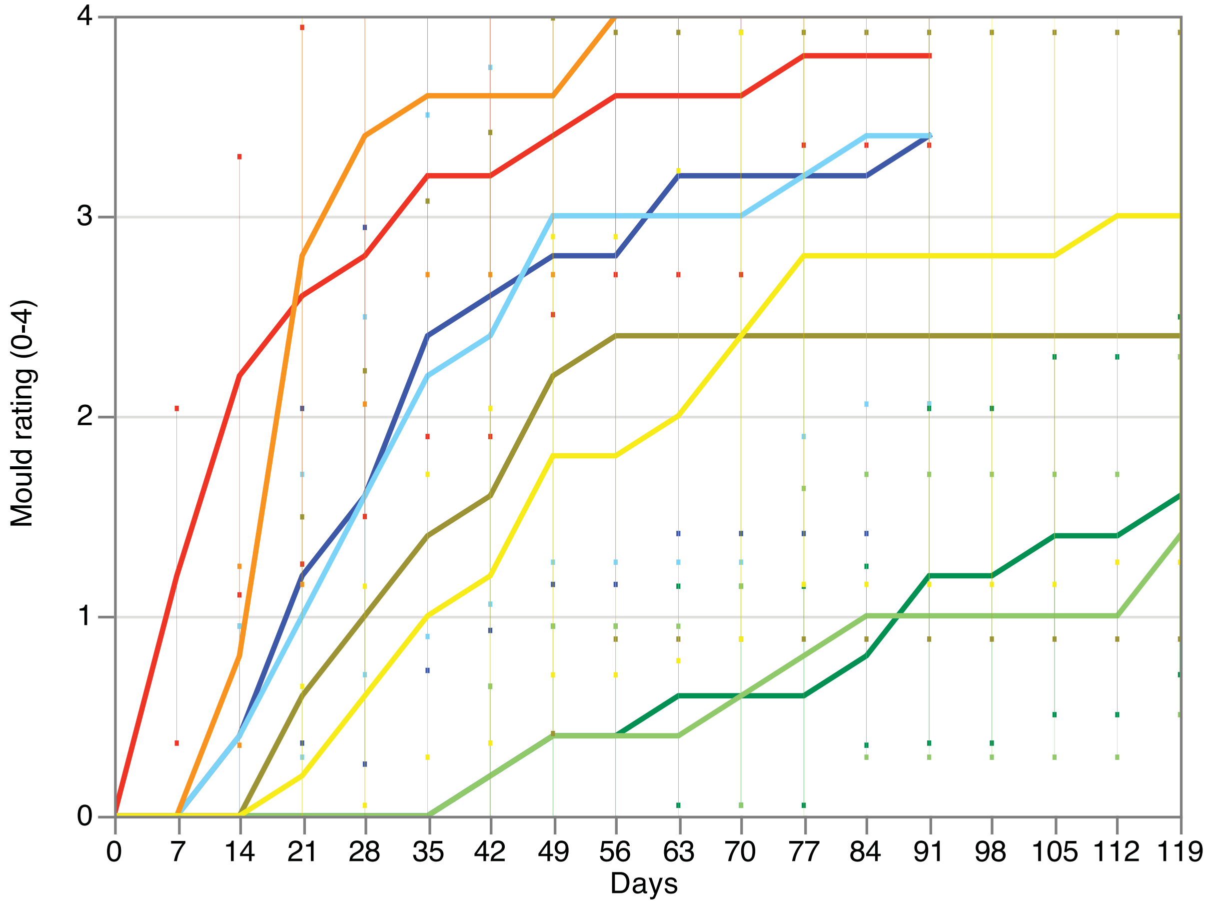

Figure 12. Mean mould rating on aspen during the exposure period.
Climate:
1: 25 °C, 85 % RH, 2h wetting period
5: 25 °C, 85 % RH, 4h wetting period
2: 10 °C, 85 % RH, 2h wetting period
6: 10 °C, 85 % RH, 4h wetting period
3: 25 °C, 65 % RH, 2h wetting period
7: 25 °C, 65 % RH, 4h wetting period
4: 10 °C, 65 % RH, 2h wetting period
8: 10 °C, 65 % RH, 4h wetting period

No significant effect of temperature on the mould rating was found in the test statistics for aspen (p = 0.9420) and there were neither any significant interaction effects of temperature and the other factors. Figure 12 shows that *climates* with same RH and wetting period, but different temperature (i.e. *climate* 1 and 2, 3 and 4, 5 and 6, 7 and 8) had similar growth curves.

After initiation of mould growth, the mould rating increased over time throughout the exposure period in most *climates*. The growth curves in Figure 12 shows that all *climates* had a lag phase, except *climate* 5 where mould rating went straight to the exponential phase. All *climates* except *climate* 3 and 4 had an exponential phase and then the growth curve seemed to flatten out more or less. In *climate* 3 and 4, the incline of the growth curve was less than in the other *climates*, and the curve did not flatten out during the exposure period.

In addition to *RH*, *wetting period* and *time*, *density* had a significant effect on the development of mould growth on aspen (Table 11). Density got a negative parameter estimate (-0.02), indicating that increased density increased the mould rating. The model presented in Table 11 got a R^2 of 0.37, RMSE of 0.56 and Misclassification rate of 0.37.

Table 11. Test statistics for the factors included in the model based on data of aspen (step 3).

Source	DF	L-R ChiSquare	p-value
RH	1	25.49	<.0001
wetting period	1	11.72	0.0006
time	1	26.51	<.0001
density	1	11.51	0.0007

When the statistical analyses were performed excluding *climate* 1, 3 and 8 (step 5), there were no considerable differences from the results presented above.

3.2.2 Scots pine

The mould growth generally initiated later and reached lower mould rating on pine heartwood than on pine sapwood (Figure 13). In the statistical model comparing all wood materials (Table 8), pine heartwood got a significantly positive parameter estimate, and pine sapwood got a significantly negative parameter estimate, indicating more mould growth on pine sapwood than on pine heartwood. Pine sapwood reached mean mould rating 1 within one week in *climate* 5 while pine heartwood reached mean mould rating 1 within six weeks in *climate* 6 (Figure 13). After 91 days, all *climates*, except *climate* 4 had mean mould rating higher than 1 on pine sapwood and the four *climates* set at 85 % RH (*climate* 1, 2, 5 and 6) had mean mould rating 1 or higher on pine heartwood. In *climate* 3, 4 and 8, all specimens of pine heartwood had mould rating 0 at the end of the exposure period.

Relative humidity and wetting period had significant effects on the mould growth on pine (Table 12). Figure 13 shows that increased relative humidity and increased wetting period had a positive effect on the mould growth. Pine heartwood reached higher mould rating in all *climates* with 85 % RH (*climate* 1, 2, 5 and 6) than in *climates* with 65 % RH (*climate* 3, 4, 7 and 8), even with the extended exposure period in *climates* with 65 % RH. This also happened to pine sapwood, except for *climate* 1 where development of mould rating was similar to *climate* 7 and 8. For pine heartwood, mould growth initiated slightly earlier and reached higher mould rating in the *climates* with 85 % RH and 4 hours wetting period (*climate* 5 and 6) than in the *climates* with 85 % RH and 2 hours wetting period (*climate* 1 and 2). For pine sapwood, mould growth initiated earlier and reached higher mould rating in the *climates* with 65 % RH and 4 hours wetting period (*climate* 7 and 8) than in the *climates* with 65 % RH and 2 hours wetting period (*climate* 3 and 4).

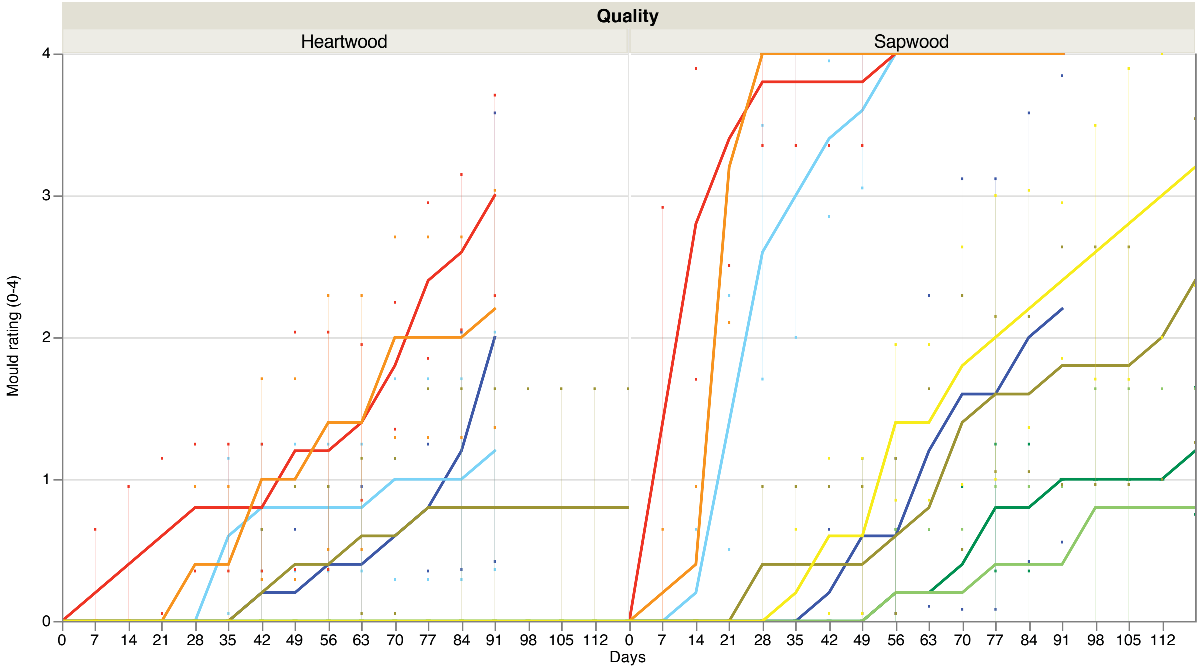

Figure 13. Mean mould rating on pine heartwood and pine sapwood during the exposure period.
Climate:
1: 25 °C, 85 % RH, 2h wetting period
2: 10 °C, 85 % RH, 2h wetting period
3: 25 °C, 65 % RH, 2h wetting period
4: 10 °C, 65 % RH, 2h wetting period
5: 25 °C, 85 % RH, 4h wetting period
6: 10 °C, 85 % RH, 4h wetting period
7: 25 °C, 65 % RH, 4h wetting period
8: 10 °C, 65 % RH, 4h wetting period

No significant effect of temperature was found in the test statistics for pine ($p = 0.3454$ for pine heartwood and $p = 0.1150$ for pine sapwood), and there were neither any significant interaction effects of temperature and the other factors. Most *climates* with same RH and wetting period, but different temperature, had quite similar growth curves, except *climate* 1 and 2 for pine sapwood (Figure 13). Specimens in *climate* 2 reached higher mean mould rating than specimens in *climate* 1.

After initiation of mould growth, the mould rating increased over time throughout the exposure period in most climates for both pine heartwood and pine sapwood. *Climate* 7 for pine heartwood was the only growth curve in Figure 13 that clearly flattened out towards the end of the exposure period.

In addition to *RH* and *wetting period*, *time* had a significant effect on the mould growth on both pine heartwood and pine sapwood (Table 12). Density had no significant effect on neither pine heartwood (p = 0.5001) nor pine sapwood (p = 0.8079).

Table 12. Test statistics for the factors included in the model based on data of pine heartwood and the model based on data of pine sapwood (step 3).

Wood material	Source	DF	L-R ChiSquare	p-value	R^2	RMSE	Misclassification rate
Pine heartwood	*RH*	1	22.80	<.0001	0.41	0.42	0.23
	wetting period	1	6.95	0.0084			
	time	1	15.63	0.0001			
Pine sapwood	*RH*	1	29.17	<.0001	0.38	0.56	0.36
	wetting period	1	13.12	0.0003			
	time	1	26.24	<.0001			

When the statistical analyses were performed excluding *climate* 1, 3 and 8 (step 5), *wetting period* was no longer significant for pine sapwood (p = 0.0642). For pine heartwood, there were no considerable differences from the results presented above.

3.2.3 Norway spruce

Both spruce heartwood and spruce sapwood got significantly positive parameter estimates in the statistical model comparing all wood materials (Table 8), indicating that spruce generally got lower mould rating than the other species. Spruce heartwood got a higher parameter estimate than spruce sapwood, and Figure 14 shows that spruce sapwood generally had more rapid growth and reached higher mould ratings than spruce heartwood.

Spruce sapwood reached mean mould rating 1 in *climate* 5 after three weeks of exposure and spruce heartwood reached mean mould rating 1 in *climate* 5 after six weeks. After 91 days, both spruce sapwood and spruce heartwood had mean mould rating 1 or higher in *climate* 2, 5 and 6, and this also occurred in *climate* 1 and 7 for spruce sapwood. During the exposure period, no mould growth was recorded on spruce heartwood in *climate* 3 and 8, and neither on spruce sapwood in *climate* 4.

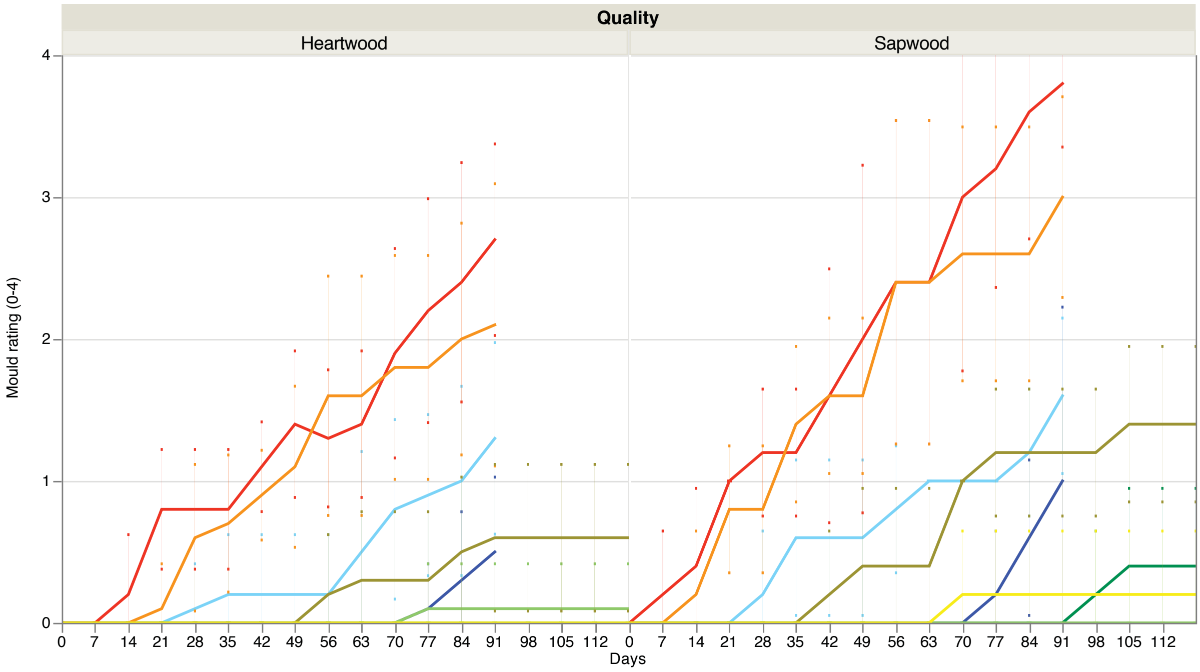

Figure 14. Mean mould rating on spruce heartwood and spruce sapwood during the exposure period.
Climate:
1: 25 °C, 85 % RH, 2h wetting period
5: 25 °C, 85 % RH, 4h wetting period
2: 10 °C, 85 % RH, 2h wetting period
6: 10 °C, 85 % RH, 4h wetting period
3: 25 °C, 65 % RH, 2h wetting period
7: 25 °C, 65 % RH, 4h wetting period
4: 10 °C, 65 % RH, 2h wetting period
8: 10 °C, 65 % RH, 4h wetting period

Relative humidity, wetting period and temperature significantly affected the development of surface mould growth on both spruce sapwood and spruce heartwood (Table 13). There was also a significant interaction effect between temperature and wetting period for spruce heartwood and between temperature and relative humidity for spruce sapwood. Figure 14 shows that increased relative humidity and increased wetting period had a positive effect on the mould growth. In three *climates* with 85 % RH (*climate* 2, 5 and 6), mould growth initiated earlier and reached higher rating than in the *climates* with 65 % RH (*climate* 3, 4, 7 and 8). Of the *climates* with 85 % RH, the *climates* with 4 hours wetting period (*climate* 5 and 6) reached higher mould rating than the *climates* with 2 hours wetting period (*climate* 1 and 3).

According to Figure 14, the same tendencies regarding the effect of temperature seemed to apply both spruce heartwood and spruce sapwood; the effects of temperature applied to *climate* 1, 2, 7 and 8, and not *climate* 5 and 6. Higher mean mould ratings were observed in *climate* 2 than in *climate* 1, and the specimens in *climate* 7 reached higher mean mould rating than those in *climate* 8. The parameter estimates showed that the interaction effect between temperature and wetness period for spruce heartwood was similar to the effect described in section 3.2.1. The effect of wetting period seemed to be larger with increasing temperature for spruce heartwood, and the effect of temperature was different at different levels of wetting period; increased temperature had a positive effect on the mould rating in the *climates* with 4 hours wetting period, and a negative effect on the mould rating in the *climates* with 2 hours wetting period. For spruce sapwood, the effect of relative humidity seemed to be larger with decreasing temperature. Higher temperature had a positive effect on the mould growth in the *climates* with 65 % RH, and a slightly negative effect in the *climates* with 85 % RH. The effect of temperature was much smaller in the *climates* with 85 % RH than in the *climates* with 65 % RH.

After initiation of mould growth, the growth curves for both spruce heartwood and spruce sapwood in *climate* 2, 5 and 6 had quite steady inclines throughout the whole exposure period. The curves for *climate* 7 seemed to flatten out towards the end of the exposure period.

In addition to the variables described above, *time* had a significant effect on the mould growth on spruce (Table 13). Density had no significant effect on neither spruce heartwood (p=0.9355) nor spruce sapwood (p=0.6454).

Table 13. Test statistics for the factors included in the model based on data of spruce heartwood and the model based on data of spruce sapwood (step 3).

Wood material	Source	DF	L-R ChiSquare	p-value	R^2	RMSE	Misclassification rate
Spruce heartwood	*RH*	1	45.86	<.0001	0.53	0.36	0.16
	wetting period	1	4.94	0.0262			
	T	1	4.93	0.0265			
	time	1	32.19	<.0001			
	*T*wetting period*	1	7.34	0.0066			
Spruce sapwood	*RH*	1	26.98	<.0001	0.53	0.42	0.23
	wetting period	1	20.46	<.0001			
	T	1	5.56	0.0184			
	time	1	23.07	<.0001			
	*T*RH*	1	5.72	0.0168			

When the statistical analyses were performed excluding *climate* 1, 3 and 8 (step 5), the only considerable difference from the results presented above was that the effect of temperature was no longer significant for neither spruce heartwood (p = 0.4756) nor spruce sapwood (p = 0.3794). The interaction between temperature and wetting period could not be tested when these *climates* were removed from the data.

3.2.4 Heartwood and sapwood

The difference in development of mould rating between heartwood and sapwood is illustrated in Figure 15 for both pine and spruce. All *climates* are included since the specimens were evenly distributed between the *climates*.

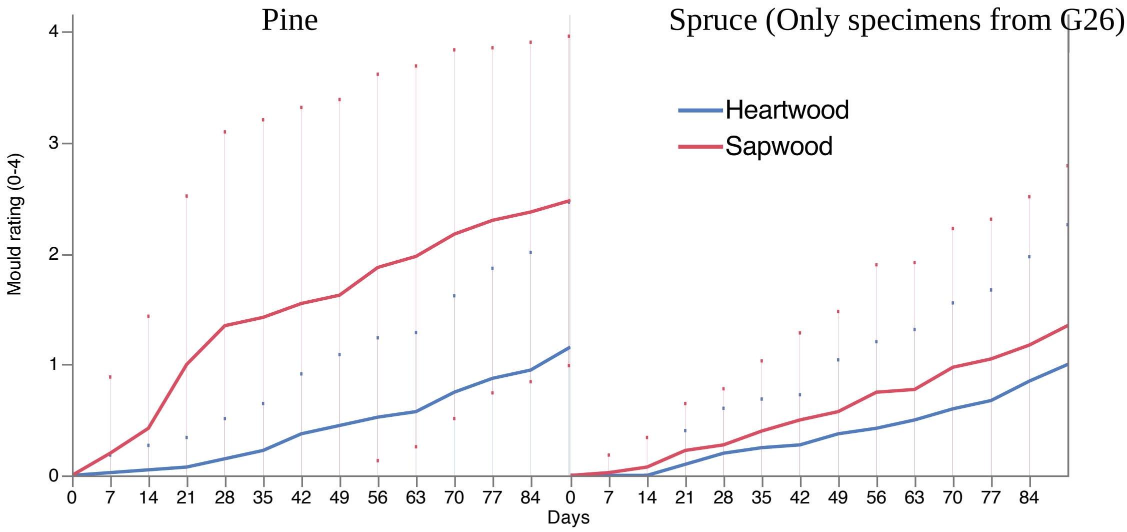

Figure 15. Mean mould rating on pine and spruce, sorted by heartwood and sapwood. Only spruce specimens from G26 are included to exclude any effect of density.

The difference between heartwood and sapwood regarding the development of mould rating was significant for both spruce and pine, but the difference was larger for pine than for spruce (Table 14). Heartwood had a positive parameter estimate for both pine (1.81) and spruce (0.74), indicating that heartwood was less susceptible to mould growth than sapwood.

Table 14. Test statistics for the factors included in the model based on data of pine and the model based on data of spruce (step 4).

Wood material	Source	DF	L-R ChiSquare	p-value	R^2	RMSE	Misclassification rate
Pine (sapwood + heartwood)	*quality*	1	34.10	<.0001	0.41	0.51	0.31
	RH	1	52.10	<.0001			
	wetting period	1	19.70	<.0001			
	time	1	41.64	<.0001			
Spruce (sapwood + heartwood) from G26	*quality*	1	4.93	0.0254	0.52	0.39	0.18
	RH	1	51.77	<.0001			
	wetting period	1	8.07	0.0045			
	T	1	4.94	0.0262			
	time	1	39.80	<.0001			
	*T*wetting period*	1	7.79	0.0053			

4 Discussion

During the exposure period, significant effects appeared for several factors investigated in this study. As expected, exposure time contributed significantly to the development of mould growth. The growth curves generally had a sigmoid shape, and this is similar to what Gobakken et al. (2010) found on untreated wood exposed outdoors. In this study, all growth phases except the phase of autolysis occurred, but there were clear differences between wood materials and between *climates* regarding the shape of the growth curves. Some *climates* seemed to not even reach the exponential phase for any wood materials. The growth decelerated towards the end of the exposure period in several *climates*, but the stationary phase occurred clearly in only *climate* 7. A longer exposure period could have shown if the mould growth would have continued until the specimens were fully covered for all wood materials, or if the curves would have flattened out earlier. In some *climates* (*climate* 3, 4 and 8), there was no or very little detected mould growth during the exposure period on the most durable wood materials. The exposure period was prolonged in the *climates* with 65 %, but there was no change in mould rating on pine heartwood (Figure 13) and spruce heartwood (Figure 14) during the additional exposure time. The relative humidity outdoors is usually not as low as 65 % over several following months (Edvardsen and Ramstad 2010). A longer exposure period in the climates with 65 % RH would therefore not be effective to investigate how surface mould growth on an outdoor facade develops over time. As mentioned above, the effects of the investigated factors were clear, so the exposure period in the rest of the climatic chambers was considered to be long enough for the aim of this study.

4.1 Factors affecting mould growth

4.1.1 Wood moisture content

In most *climates*, the specimens accumulated moisture the first days of the exposure period before the MC was quite stable the rest of the exposure period (Figure 10). This was as expected because the ability to desorb water increases with increasing MC (Siau 1984), and the curve therefore stabilized after some increase in MC. During the stable period it is assumed that the specimens absorbed the same amount of water during the wetting period that was desorbed during the rest of the day. There was an unexpected peak in MC after some weeks of exposure in *climate* 2, 6 and 8 (Figure 10). Finding the right settings for the air-regulating system in the climatic chambers was challenging, especially in *climates* with 10

°C, and this probably led to a higher relative humidity and higher MC during the first weeks of exposure.

In this study, the MC significantly affected the mould growth (Table 9). Higher MC generally led to higher mould rating. The measured MC was useful to investigate how the different levels of the factors affected the mould growth, and it gave an indication of whether the specimens dried between the wetting periods or if the specimens accumulated water. Allowing the specimens to dry up between the wetting periods was not sufficient to avoid mould growth on the most sensitive wood materials. This supports earlier findings showing that mould growth may be initiated if dry conditions are interrupted by wet conditions 3 - 4 hours per day (Adan 1994; Sedlbauer 2001).

The measured mean MC gave no precise prediction of the mould growth. The values for R^2, RMSE and misclassification rate were poorer for the statistical model using mean MC and exposure time as explanatory variables than the model using wood material, relative humidity, wetting period and exposure time as explanatory variables. The MC was measured as the mean of the whole specimen, and the measurements were done only once a week. The conditions of the specimen's surface are more important for the surface moulds than the mean of the whole specimen. The lowest mean MC for reaching mean mould rating 1 (within 91 days) in one *climate*, was 10.0 - 20.7 % (Figure 9 compared with Figure 11), depending on wood material, which is a quite broad interval. This is similar to earlier research on fungal decay, where the lowest MC for fungal growth was between 12.3 - 24.5 % with an external moisture source (Meyer and Brischke 2015). Mould growth is different from fungal decay, but this tells us that it generally may be challenging to estimate critical MC for fungal growth when wood is periodically wetted.

4.1.2 Relative humidity

Relative humidity was the most important climatic factor affecting mould growth in this study (Table 11 – 13). Increased relative humidity had a positive effect on the mould growth. This supports earlier findings showing that the mould growth rate increases with increasing humidity (Block 1953; Ayerst 1969; Viitanen 1996; Sedlbauer 2001). Increased relative humidity generally increased the moisture content of the specimens. The *climates* set at 85 % RH had higher moisture content during the exposure period than the corresponding *climates* with 65 % RH (Figure 10), which is expected since wood is a hygroscopic material.

During the exposure period, the relative humidity probably varied somewhat from the set values in several *climates* (Table 4 and 5). The measurements of relative humidity in *climate* 1 and 3 were done after the exposure period was finished, but the calculated wood moisture content (Figure 10) shows that deviations probably also occurred during the exposure period. There may also have been some uncertainty with the measuring equipment, so the values for relative humidity should not be used as exact values. However, the effect of relative humidity was still significant for all wood materials when the statistical analyses were performed without *climate* 1, 3 and 8. The relative humidity was used as a categorical variable, and the actual level between the climatic chambers set 65 % RH and the chambers set at 85 % RH was considered to be large enough to only categorize the relative humidity in two levels in the statistical analyses, and draw general conclusions about how it affected the development of surface mould growth.

Because of the deviations mentioned above, and because the specimens were sprayed with water, a critical limit for relative humidity was hard to find in this study. A test design with only two levels of the factors also limits the possibility to find a precise critical limit. Mould growth occurred on several wood materials in the *climates* set at 65 % RH, and this supports the assumption that moulds are able to grow in dry conditions if the time of wetness is long enough. The growth curves for pine sapwood showed however an interesting trend supporting the hypothesis that humidity conditions corresponding to 80 % RH are the critical limit for mould growth on wood (Adan 1994; Gobakken et al. 2010; Sedlbauer 2001; Viitanen et al. 2011). The growth curves for pine sapwood (Figure 13) were divided into two groups; one with mainly *climates* set at 65 % RH and one with mainly *climates* set at 85 % RH. However, *climate* 1 which also was set at 85 % RH, but probably had 80 % RH or below, had mould growth more similar to the *climates* set at 65 % RH. The critical limit may be lower for aspen than for pine sapwood. For aspen, all the *climates* set at 85 % had more mould growth than *climates* set at 65 %, and *climate* 1 had mould growth almost parallel to *climate* 2 (Figure 12), which is different from the growth curves for pine sapwood. This supports earlier findings showing that different materials may have different critical limits (Johansson et al. 2012). An experiment without water spraying and with more levels of relative humidity is required to determine the critical levels for the different wood materials.

4.1.3 Wetting period

The wetting period had a significant effect on the development of mould growth on all wood materials in this study (Table 11 - 13). Longer wetting period had a positive effect on the mould growth. The *climates* with longer wetting period had higher moisture content during the exposure period than the corresponding *climates* with shorter wetting period (Figure 10). A longer wetting period gave the specimens less time to dry, which increased the time of wetness for the specimens. When the statistical analyses were performed without the deviating *climates* (*climate* 1, 3 and 8), wetting period was no longer significant for pine sapwood. Wetting period may have smaller effect on pine sapwood than the other wood materials, but this should be validated against new data before it is concluded.

Mould growth occurred on specimens of aspen and pine sapwood at 65 % RH with 2 hours of wetting per day. For pine heartwood and spruce heartwood, not even 4 hours of wetting per day were enough to cause mean mould rating higher than 1 in any of the *climates* set at 65 % RH during the exposure period. Spruce sapwood reached mean mould rating 1 in one of the *climates* set at 65 % RH with 4 hours wetting period. Overall, the results from this study corresponds well with previous research indicating that time of wetness of 3 - 4 hours per day can be critical (Adan 1994; Sedlbauer 2001). However, it is clear that there are differences between materials, and one should take this into consideration when comparing the results. Shorter time of wetness may be critical for sensitive wood materials such as aspen and pine sapwood, and it would be interesting to test even shorter wetting periods, e.g. one hour per day, and see if mould would still grow on the most sensitive species.

The water spraying was a useful tool to investigate what happens in cases where the surface is periodically wetted without increased relative humidity in the surrounding environment. However, it should not be regarded as the same as outdoor precipitation. The water spraying was intended to mimic the wetting of wood resulting from condensation. Rain can be much heavier and may even wash off the moulds, and wetting of facades may occur in cases of fog and decrease in temperature without there being any precipitation. Further study about the effect of different water spraying intensities (e.g. tough spray versus light mist) may simplify the prediction of the appearance of a building facade over time.

4.1.4 Temperature

The temperature was the least significant climatic factor in this study. Temperature had a significant effect on the mould rating in the statistical analysis where data of all species were included (Table 7), but the separate analyses of all wood materials showed that this only applied to spruce heartwood and spruce sapwood (Table 11 - 13). Interaction effects between temperature and the other factors were also only significant on spruce. The effects of temperature were most prominent in *climate* 1, 2, 7 and 8, but the RH probably deviated from the set value in two of these *climates* (1 and 8), which made it difficult to determine whether it was the temperature or the other factors that affected the mould growth. When the statistical analyses were performed without *climate* 1, 3 and 8, temperature was no longer significant in any of the tested models. This made it challenging to draw any conclusions about the effect of temperature based on the statistical analyses.

Although the temperature overall seemed to have little effect on the mould growth, it probably had an effect on the wood moisture content. Lowering the temperature decreases the wood drying rate, and this led to higher wood moisture content during the exposure period (Figure 10). The temperature may also have affected the actual relative humidity in the climatic chambers because of the water spraying. This was especially evident in *climate* 8, set at 10 °C, 65 % RH and 4 hours wetting period. The air-regulating system in the chambers struggled to remove the moisture supplied during the water spraying. Since colder air have less ability to hold moisture than warm air, the relative humidity increased more during the water spraying in the *climates* with 10 °C than in the *climates* with 25 °C.

Earlier research has shown that humidity in general may affect fungal development more than what temperature does (Viitanen and Ritschkoff 1991). According to this theory, the specimens in the colder *climates* should have had more mould growth than the specimens in the warmer *climates*, since the colder climates generally had higher wood moisture content. This did not happen in all cases in this study, which was especially evident in *climate* 7 and 8. For pine heartwood (Figure 13), spruce heartwood and spruce sapwood (Figure 14), *climate* 7 reached higher mould rating than *climate* 8, although the wood moisture content (Figure 11) and measured relative humidity (Table 4) was generally higher in *climate* 8 than in *climate* 7. Hence, it seems that a higher temperature actually had a positive effect on the moulds metabolism, and this effect was probably larger under less favourable conditions (more durable wood materials and less humid *climate*s). For each wood material in this study, the growth curves for the two *climates* with 85 % RH and 4 hours wetting period were nearly identical, and this supports the findings by Viitanen and Ritschkoff (1991), suggesting that the effect of temperature on mould growth is suppressed at high humidity levels.

As mentioned in the introduction, different moulds have different optimum temperatures, and the results therefore depend on which moulds are present. The spore suspension used in this study was made of three fungi and what actually grew on the specimens was not examined. Both *Cladosporium cladosporioides* and *Aureobasidium pullulans* are known to have optimum temperature between 25 and 30 °C (Käärik 1980; Sedlbauer 2001), but moulds from *Ulocladium* may favour a colder environment (Mattsson 2004). The presence of *Ulocladium* may thus have been a contributing factor to the low significance of temperature in this study, and identifying which fungi actually were present on the different specimens could have revealed this.

4.1.5 Wood properties

Wood material

In this study, aspen and pine sapwood were most susceptible to mould growth. Pine heartwood and spruce heartwood were least susceptible to mould growth. The water permeability and the content of nutrients and extractives may explain some of the differences in durability against mould growth. A more permeable material has a more open structure and absorbs water more rapid. During the water spraying, the more permeable species may have absorbed enough moisture to increase the time of wetness of the wood surface and therefore increase the mould growth. Aspen and pine sapwood had highest MC in several *climates*, but lowest MC in the driest and warmest *climates*. The calculated MC is based on weight measured several hours after the water spraying. The exact amount of absorbed and desorbed humidity for each specimen is therefore not known, but the more permeable wood species have presumably reached a higher MC during this period.

The differences between species may be smaller under more favourable conditions and the differences between species may be evened out over longer time. *Climate* 5 seemed to have very favourable conditions for the moulds used in this study. The differences between species were smaller in *climate* 5 than the other *climates*. Rüther (2011) found no difference in mould rating between Norway spruce, Scots pine and aspen after three and a half year of outdoor exposure facing west; all species had achieved the highest possible mould rating (growth on over 70 % of the surface). West was the cardinal point with the most mould growth in the study (Rüther 2011).

Density

In this study, density had significant effect on mould growth on aspen, but not the other species. This study was only designed to test the effect of density on the spruce specimens, and density was therefore not expected to have a major effect on aspen and pine. Increased density significantly increased the mould rating on aspen, but the results may have been influenced by other wood properties. The heartwood proportion in the specimens of aspen was not known so the density may have been confounded with this. Although heartwood and sapwood of aspen are visually similar, there may be differences in the physical properties; heartwood of aspen may be less permeable than sapwood of aspen (Wengert 1976). However, the result in this study showing that density had no significant effect on the mould growth on spruce is interesting, and supports previous research stating that high density does not necessarily mean high resistance against fungi (Brischke et al. 2006; Gobakken et al. 2011).

Heartwood and sapwood

Sapwood was significantly more susceptible to mould growth than heartwood for both pine and spruce in this study (Table 14). Since no effect of density was found for pine and spruce, the assumptions that heartwood proportion is more important than density for the resistance against moulds are strengthened. The results showing that pine sapwood was more susceptible to mould growth than pine heartwood corresponds with the findings of Blom et al. (2013). Pine sapwood is known to be more permeable than pine heartwood (Øvrum and Flæte 2008), and the measured mean MC corresponds well with this; the MC during the exposure period was higher in pine sapwood than pine heartwood in several of the studied *climates*, but the MC was lower for pine sapwood than pine heartwood in *climates* where the specimens got the chance to dry (Figure 11). The low permeability combined with the increased extractive content may explain the increased durability for pine heartwood.

Results showing that spruce sapwood may be more susceptible to mould growth than spruce heartwood have also been found in earlier studies (Sandberg 2008; Blom et al. 2013). Spruce sapwood had slightly higher mean MC than spruce heartwood in several *climates* (Figure 11). This supports earlier research indicating that spruce heartwood is less permeable than spruce sapwood (Sivertsen and Vestøl 2010). The difference in mean MC between spruce heartwood and spruce sapwood was largest in *climate* 5, 6 and 7. These *climates* were also the ones with largest difference in mean mould rating between spruce heartwood and spruce sapwood after 91 days (Figure 9).

4.2 Evaluation of surface mould growth

Mould rating is most often based on visual evaluations (Gobakken et al. 2009), and this may vary from one evaluator to another. In different studies, different evaluators make the evaluations, and different studies may also use different rating scales. In this study, mould rating 1 was defined as “up to 10 % growth on the surface of the specimen”. Examples of other definitions of mould rating 1 are: “Small amounts of mould on surface (microscope), initial stages of local growth” (Viitanen et al. 2011 p. 4), “Little, or very scattered, growth” (Thelandersson et al. 2009 p. 14) and “No mould growth” (Rüther 2011 p. 63). What is considered as critical mould growth also varies between studies (Johansson 2012). When comparing results from different studies, one must therefore take this into consideration. To investigate the effect of various factors the most important is however that the same scale is used throughout the test and that the same evaluator makes the evaluations.

The mould rating scale used in this study is only based on how much the surface of the specimen is covered with mould growth, and not the shape and pattern of the growth. Therefore, two specimens with the same rating may have different visual appearance. The highest mould rating state that minimum 50 % of the specimen’s surface has to be covered with mould, and therefore it is not investigated how the mould continued to grow after reaching mould rating 4.

To achieve the most reliable results, it is always preferable to use as many replicates as possible during an experiment. In this study, five replicates of each material were tested. In NS-EN 15457 (Standard Norge 2014), three replicates are used. More specimens would have given a more reliable result, but limits had to be set and the number used was considered adequate to investigate the topic of this thesis.

Three mould cultures were used in the spore suspension used in this study. In nature, there are several more mould species and the required growth conditions of these may vary from the studied moulds. In this test, different mould species may also have occurred from the surrounding air. The moulds used in this study were chosen to represent moulds commonly occurring outdoors, and by including three fungal species some variation was obtained. The spore suspension was evenly distributed on the specimens, and in an outdoor environment the spores have to come from the surrounding air, which may require more time. In laboratory tests, there is limited time and it is important that the spores are actually present in order to investigate the effects of various factors affecting mould growth.

5. Conclusion and future aspects

Increasing the exposure time, wood moisture content, relative humidity and wetting period significantly increased the mould growth, and relative humidity was more important than wetting period. Temperature was only significant for the development of surface mould growth on spruce, and not for the other species. Lowering the temperature decreases the wood drying rate and this may have counteracted the effect of a higher temperature on the moulds metabolism. There were significant differences between wood materials. Heartwood of pine and spruce were least susceptible to mould growth and aspen and pine sapwood were most susceptible to mould growth. Heartwood was significantly less susceptible to mould growth than sapwood for both pine and spruce. Density affected mould growth only on aspen but the heartwood proportion was not known for aspen and this may have had a confounding effect.

Future aspects

- By conducting similar experiments with more levels of the affecting factors, critical levels may be found and reliable models can be developed. When investigating how the different factors affects mould growth, the actual growth conditions (e.g. relative humidity and temperature) should be measured continuously in order to quantify the critical values one may look for.
- Investigating factors affecting surface mould growth should also be done on untreated wood exposed outdoors to verify the results obtained in this study. The development of mould growth should be frequently evaluated in order to provide knowledge about how a facade will change over time.
- Wood moisture content can be investigated further to explain the variability of the durability of wood. Especially the surface's MC and time of wetness may be interesting to compare with the development of mould growth.
- Norway spruce proved to have relatively slow mould growth in this study. A further investigation of this may lead to an even better reputation for Norway spruce as a durable cladding material.

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