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Published in:
IRG56 Scientific Conference on Wood Protection : Yokohama, Japan, 22 - 26 June, 2025

2025

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Niklewski, J., & Brischke, C. (2025). A multi-dataset validation study of moisture prediction in Norway spruce wood exposed outdoors. In *IRG56 Scientific Conference on Wood Protection : Yokohama, Japan, 22 - 26 June, 2025* (Vol. 2025). (Proceedings IRG Annual Meeting; Vol. 2025). International research group on wood protection.

Total number of authors:
2

Proceedings IRG Annual Meeting (ISSN 2000-8953)

IRG/WP 25-41029

THE INTERNATIONAL RESEARCH GROUP ON WOOD PROTECTION

Section 4 **Applications and Performance**

A multi-dataset validation study of moisture prediction in Norway spruce wood exposed outdoors

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Paper prepared for the IRG56 Scientific Conference on Wood Protection
Yokohama, Japan
22 – 26 June, 2025

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A multi-dataset validation study of moisture prediction in Norway spruce wood exposed outdoors

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ABSTRACT

Wood used in outdoor construction undergoes continuous cycles of wetting and drying, resulting in fluctuating moisture contents that directly influence its long-term durability. Excess moisture above a critical threshold leads to deterioration by fungal decay, limiting the service life of the structure. Service life models thus rely on accurate predictive models of moisture behaviour. However, capturing the complexities of free water movement in real-world scenarios – where environmental factors such as rainfall and humidity vary unpredictably – remains a major challenge. Numerical approaches, particularly diffusion-based models grounded on Fick's laws, have been used for this purpose. However, these models have not yet undergone comprehensive validation under relevant outdoor conditions. The present study directly addresses these issues by validating a single numerical model configuration across multiple datasets, including both gravimetric and point-type moisture measurements taken at the wood surface and in the core. This comprehensive validation approach seeks to ensure that the model not only predicts overall moisture fluctuations but also captures the internal distribution of water. Results indicate good agreement between simulated and observed moisture content, though further exploration under more diverse climatic conditions is recommended for further validation. Ultimately, by validating the numerical model across multiple datasets, this study evaluates the model's predictive performance, reveals the conditions under which higher bias may arise, and examines how that bias translates into service life predictions.

Keywords: moisture, wood, validation, numerical, measurements, weathering

1. INTRODUCTION

Wood used in outdoor construction is consistently subjected to cycles of wetting and drying, leading to varying moisture levels that impact its long-term durability. High moisture content, especially if sustained above a certain threshold, promotes fungal decay and structural degradation (Brischke and Thelandersson 2014). Modelling moisture behaviour in wood exposed to rain and changing humidity is crucial for predicting decay risks, particularly as wood is increasingly used in sustainable construction. Therefore, accurately predicting moisture content over time is essential for assessing the durability of wood and for making informed decisions in the design and maintenance of timber structures.

Numerical approaches, such as diffusion-based models, have been widely used to predict moisture distribution within wood. For instance, Fick's laws of diffusion have been applied to simulate moisture transport in the hygroscopic range, allowing researchers to estimate moisture profiles under laboratory and outdoor conditions (Angst and Malo 2010). However, accurately capturing the nuances of free water transport, especially under fluctuating weather conditions, remains challenging. Factors such as the boundary conditions of the model (*e.g.*, surface saturation during rainfall) and the additional complexity of free water flow introduce uncertainties to diffusion-based models. Nevertheless, several prior studies have successfully modelled moisture transport of water exposed wood in laboratory conditions (Derbyshire and Robson 1999, De Meijer and Militz 2000, Virta *et al.* 2006) and outdoor conditions (Niklewski and Fredriksson, 2021). Recent advancements with multi-phase models, where free water is modelled explicitly, have also shown promising results (Brandstätter *et al.* 2025).

A significant limitation in many of these studies is their reliance on limited data for calibration and validation, which may not fully capture the range of environmental conditions wood is likely to encounter in real-world applications. One problem is that studies capturing moisture variations in wood use different experimental designs and techniques for instrumentation, the most common being gravimetric and resistance based. Gravimetric measurements can be used to confirm that the average moisture content is modelled correctly, but measurements are usually not continuous and offer only a snapshot of the moisture state. Resistance-type sensors are commonly continuous but are limited to specific depths. In addition, as an indirect measure they are associated with higher measurement uncertainty than gravimetric measurements. Another challenge is that moisture dynamics change as the wood is subject to deterioration (Brischke *et al.* 2019), so the bias of a static model may drift over time.

Models that are calibrated to one specific dataset may not perform well in general. A numerical model that describes a physical process is, unlike a data-driven model, flexible in its application. However, simple models such as the one used by Niklewski and Fredriksson (2021) should not be seen as generalisable, and therefore still rely on calibration and extensive validation. For example, model performance compared against gravimetric measurements does not necessarily transfer to a different dataset where moisture content was measured at a specific depth.

To address this gap, the present study aims to validate a numerical model for predicting moisture content in wood by testing it against multiple datasets, including gravimetric and point-type measurements on the wood surface and in the core. The goal is to demonstrate that a single model configuration can accurately predict moisture dynamics in wood across several types of datasets. By verifying the model against multiple sources, this study seeks to provide a solid foundation for the broader application of moisture prediction in durability assessments, ultimately supporting the design of moisture-resilient, sustainable wood structures in different climatic contexts.

2. MATERIALS AND METHODS

2.1 Numerical model

The variation of the numerical model that will be used across all validation datasets is taken from an earlier study by Niklewski and Fredriksson (2021). The numerical model is based on Fick's second law of diffusion and describes the transport of moisture through the material. The equation governing the transport is given by:

$$\frac{du}{dt} = \frac{d}{dx}\left(D\frac{du}{dx}\right) \qquad (1)$$

where u (kg/kg) is the moisture content and D (m^2/s) is the diffusion coefficient, which governs the rate of transport. The model is single-phase, which means that the three different phases of water (bound, vapour, free) are unified to a single quantity with a single transport coefficient. This coefficient is temperature dependent and, more importantly, strongly dependent on moisture content. The function employed here, shown in Fig. 1a, was determined experimentally by Koponen (1984).

Wood is hygroscopic, meaning it absorbs or releases moisture to match the surrounding air. The driving force is the difference in water vapour pressure between the wood surface and the ambient environment. Over time, the wood surface strives to balance these pressures and reaches an equilibrium moisture content where no net water exchange occurs. The equilibrium condition is generally described by the sorption isotherm, as shown in Fig. 1b, and the rate of exchange is described by the following equation:

$$\ldots.. \; q = k_p(p_{vw} - p_v) \tag{2}$$

where q (kg/m^2 s) is the moisture flux, k_p (kg/m^2 Pa s) is the mass transfer coefficient, p_{vw} (Pa) is the vapour pressure on the wood surface and p_v (Pa) is the vapour pressure of the ambient air. As such, the difference (p_{vw}–p_v) is the driving force which becomes zero at equilibrium. The vapour pressures are calculated from the relative humidity of the air and from the equilibrium relative humidity, as obtained from the sorption isotherm. The sorption isotherm used by this specific model, shown in Fig. 1b, was fitted to measurements of Fredriksson and Thygesen (2017) up to 99% relative humidity.

When the wood surface is exposed to free water, it is assumed that the boundary immediately reaches the maximum moisture content, u_f (kg/kg), and remains at this value until wetting stops. The value is not set equal to the theoretical point of saturation but has been used as a calibration parameter to control the total amount of water ingress against experiments. When wood is exposed to single-sided wetting, such as in a floating test, the mass of absorbed water tends to be linearly proportional to the square root of time, $\sqrt{t}$. The constant of proportionality is the absorption coefficient, which for Norway spruce (*Picea abies*) in the tangential direction varies approximately between about 2 and 4 (g/m^{2}s$^{0.5}$) in the literature (Niemz *et al.* 2010). These coefficients are approximately reproduced by assigning the boundary to 60% and 120% moisture content, respectively, as shown in Fig. 1c. In this study, all simulations are run with both values to produce a range of results. The sorption isotherm is set to the maximum moisture content at 100% relative humidity with linear interpolation from 99%, as shown in Fig. 1b.

The model requires hourly or higher resolution weather data. As aforementioned, the maximum moisture content, u_f, is assigned for the whole duration of rain events. The duration of rain events is difficult to estimate from hourly weather data. In this model, a simple linear relationship based on a limited amount of high-resolution data is used:

$$t_f = \min(0.5p; 1) \tag{3}$$

where t_f describes the duration of the rain event by a value between 0 (no rain) and 1 (full hour of rain) and p is the hourly precipitation. Consequently, it is assumed that any hour with more than 2 mm of precipitation corresponds to a full hour of water exposure on rain-exposed surfaces.

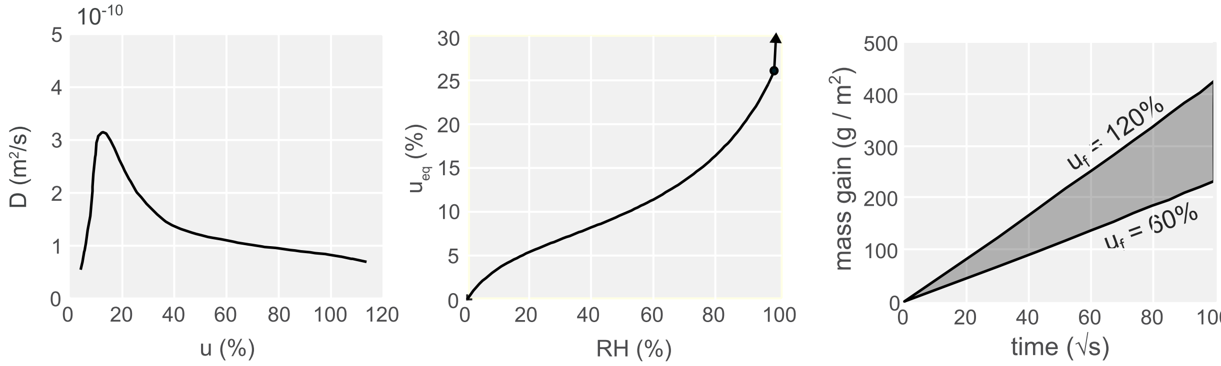

Figure 1. Diffusion coefficient at 20° C (left), sorption isotherm (centre) and absorption under constant single-sided wetting and two different surface moisture contents (right)

2.2 Experimental datasets

This section describes each experiment in brief, with focus on the smaller set of data that was used for the present study. Data from a total of five different experiments were used, hereafter referred to as Hannover A (Brischke *et al.* 2017), Hannover B (Meyer-Veltrup *et al.* 2017), Lund A (Isaksson and Thelandersson, 2013), Lund B (Niklewski *et al.* 2018b) and Lund C (Niklewski *et al.* 2023). As indicated by the names, two experiments were conducted in Hannover, Germany and three were conducted in Lund, Sweden. The accumulated period of all five experiments exceeds 10 years.

2.1.1 Hannover A

Brischke *et al*. (2017) conducted an experiment aiming to assess the moisture-induced risk for decay in wooden façades and decking by monitoring moisture content and temperature, and to develop a time-saving method for durability classification and service life prediction. The experiment included several wood species, and most specimens were monitored over a total of six years. The horizontal decking boards (n=3, 25 x 100 x 500 mm) made of Norway spruce which were used in the present study were monitored over the whole duration, but only three years of data was used here. The test was conducted on a rooftop at a height of 18 m from the ground level. No protective sealant was applied to the board end-grain or other sides.

The moisture content was measured using a commercial resistance-based system (Product name: Scanntronik Materialfox Mini) with custom electrodes. The electrodes were made from polyamide coated stainless steel cables with a core diameter of 1.2 mm, which was glued with conductive adhesive at the bottom of a predrilled hole of 4 mm diameter. The first 5 mm of plastic coating were removed from the electrode prior to glueing. After 24 hours of hardening, the hole was filled by non-conductive glue. The resistance characteristics (calibration curves) were developed in earlier works by the same group (Brischke *et al.* 2008, Brischke and Lampen 2014). The resistance was measured over 30 mm in the grain direction, with a displacement of 6 mm orthogonal to grain to reduce the risk of cracking.

2.1.2 Hannover B

Meyer-Veltrup *et al.* (2017) conducted an experiment to evaluate different test methods for durability assessment of wood exposed above ground by comparing moisture performance and decay development across various exposure setups. The experiment included several wood species and many types of accelerated field setups. The specimens were exposed on ground level and the exposure period was about three years. The subset of data used for the present study includes boards of Norway spruce (*Picea abies*) from two different setups (n = 6 total, 20 x 100 x 500 mm). The main difference between the two setups was that one set (n = 3) was elevated a bit more from the ground level, providing better conditions for drying. No protective sealant was applied to the board end-grain or other sides.

The moisture content was monitored using the same system as described under section 2.1.1 (Hannover A), including the sensor type, calibration curve and electrode design. In addition, the weather data was obtained from the same station.

2.1.3 Lund A

Isaksson and Thelandersson (2013) conducted an experiment to investigate the effect of detail design and exposure conditions on the moisture variation in wood. The referenced paper describes the first year of data. After one year, the experimental setup was repurposed with new details and run for another year. Data from the second stage was never published in full. The horizontal boards (n = 2) used as reference were monitored continuously over both periods. Therefore, about 2.5 years of data were available for the present validation.

The moisture content was monitored using a commercial resistance-type moisture sensor (Product name: Omnisense type S-1). The sensor was wired to two Teflon-insulated nails with an uninsulated tip, acting as electrodes. The nails were pushed to the centre board thickness, where the resistance was measured once per hour over 30 mm in the grain direction. In the original publication, Isaksson and Thelandersson (2013) used a calibration curve from Samuelsson (1990). However, a later calibration including several other curves from the literature found a curve by Hjort (1996) to be more accurate. This same calibration curve is used for all three datasets originating from Lund, Sweden.

In addition to the above sensor, the boards were equipped with a different resistance-based system for detecting the presence of surface moisture, developed by Fredriksson *et al.* (2013). A pair of capillary tubing (diameter 1 mm) was pushed through pre-drilled holes (diameter 1.6 mm) from the bottom face to level with the top face. Two copper wires soaked in conductive adhesive were then pushed through the capillary tubing. The electrodes were intended to be fully electrically insulated from the dry wooden substrate and only connect when water bridged the capillary tubing.

A weather station was available on the test site, monitoring relative humidity, temperature and precipitation with every 10 minutes. The first year had almost complete data coverage. During the second year, station outage caused gaps in the weather time-series which were filled by nearby weather stations.

2.1.4 Lund B

Niklewski *et al.* (2018b) performed an experiment to investigate how different detailing affect the moisture content of rain-exposed glue-laminated timber (glulam) members made of Norway spruce. A total of 11 glulam beams (115 × 270 × 3200 mm) and 9 columns (115 × 115 × 2000 mm) were exposed on a rooftop with minimal shelter from wind, rain and solar radiation and a height above ground of about 10 m. Various connection details, including steel details, wood-to-wood contact areas, and exposed end-grain, were incorporated to examine their moisture-trapping effects. For the present study, only measuring points on horizonal beam surfaces (n = 3) were used.

To measure the moisture content, the study used the same resistance-based sensors, insulated nails and weather station as Isaksson *et al.* (2013). The nails were pushed to a depth of 10 mm from the surface and the resistance was measured over 30 mm in the grain direction. In addition to these measurements, uninsulated electrodes were pushed to a depth of about 5 mm to measure moisture content at and near the wood surface.

2.1.5 Lund C

The experiment conducted by Niklewski *et al.* (2023) compared pre-weathered and freshly planed specimens to evaluate differences in moisture uptake and drying behaviour. The experiment involved exposing Norway spruce boards (250 x 100 x 25 mm) to outdoor conditions for 12–18 months. Boards with sealed short edges were mounted on a 30-degree inclined rack facing south, exposing one face to precipitation and solar radiation. The exposure start dates of different sets of specimens were varied, to assess the progressive effects of weathering. A single set consisted of three axially matched specimens, including one pre-weathered and two freshly planed boards. At the end of the exposure period, all specimens were sheltered from precipitation for six months by covering the setup with a ventilated plastic sheeting.

Moisture content was measured every 5 minutes by the same resistance-based system as Isaksson and Thelandersson (2013). However, a custom-made electrode design consisting of a threaded rod (α=2 mm) with a sharp pointed end and non-conductive glued shrink tubing was used. The uninsulated pointed end was approximately 5 mm. To install an electrode pair, two small holes (diameter 1.5 mm) were drilled from the top face with a spacing of 30 mm across the grain. The smaller holes were then expanded by using a larger drill bit (3 mm) and drilling from the back face to a depth of 3 mm less than the total thickness of the board. Electrodes were then coated by non-conductive silicone-based glue and carefully inserted through the back face, so that the uninsulated pointed end penetrated the top surface. The design of electrode and setup was first tested in a laboratory study by Niklewski *et al.* (2018a) where it performed well when compared against parallel measurements of surface wetness by image analysis. In addition to the surface measurements, all boards were weighed at biweekly intervals.

The study in question successfully documented differences in surface conditions between weathered and planed specimens. However, this difference became rather subtle after a few months, when the planed specimen had become weathered. At the end of the test, when all specimens were at least moderately weathered, the variability between specimens was rather small. Based on these observations, we did not differentiate between weathered and non-weathered specimens, and for comparison against surface measurements we limited our analysis to the first set of specimens for the purpose of the present study. In the comparison against gravimetric measurements, we included all specimens but removed the first two weeks of measurements for each set except for the first one.

2.3 Weather data

Weather data for all experiments were available from nearby weather stations. The five different datasets are shown in Fig. 2 on a common timeline. The data used for validation include hourly values of relative humidity, temperature and precipitation. Weather data had been checked against other sources to verify accuracy, and in some cases, segments were substituted with data from another nearby station to fill a gap caused by outage or dubious data.

The five experiments were conducted in northern European climates featuring high relative humidity (often exceeding 90%) and low temperatures (frequently around 0 °C) during the cold season. Snowfall data were not explicitly collected, but it is common for horizontal wood surfaces to be covered in snow at times. Because the locations were relatively close to each other geographically and the experiments partly overlapped in time, the climate variability across the experiments was limited. Consequently, while the study benefits from an extensive data set, the narrow environmental range reduces the generalisability of the model to other climatic regions. Put simply, the findings and model performance are robust within these specific conditions, but caution is warranted when extrapolating to climates that differ substantially in temperature and humidity.

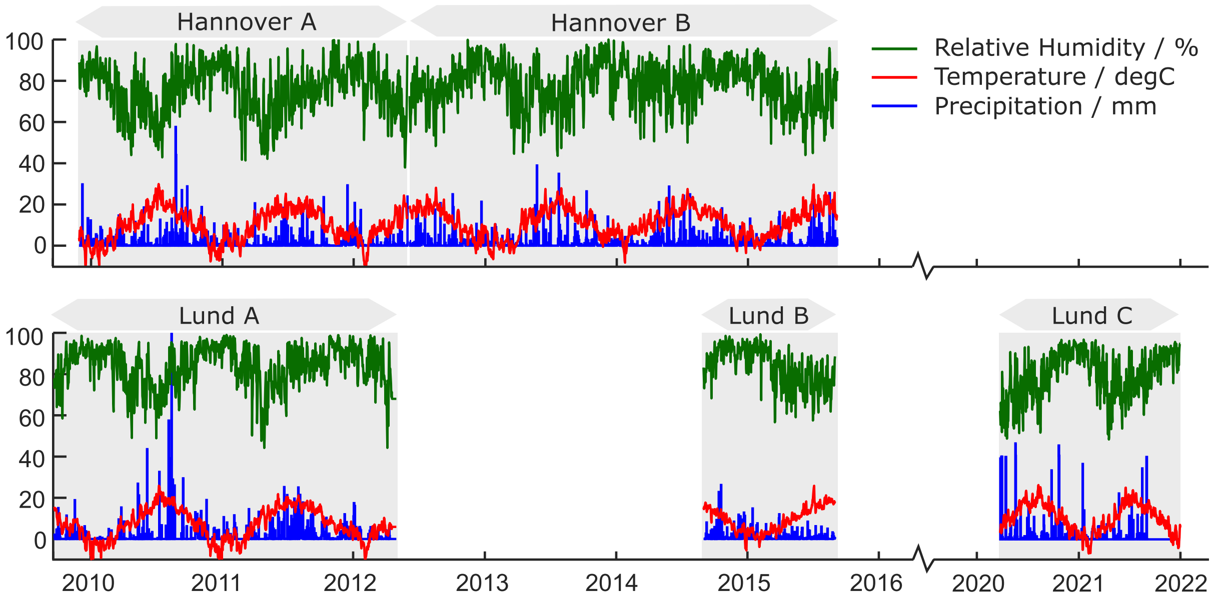

Figure 2. Daily weather data from the five different experiments from Hannover (top) and Lund (bottom) shown on a common timeline.

2.4 Numerical assumptions

All simulations simplified and performed in one dimension. This implies that no moisture transport occurs in the longitudinal direction or towards the short sides. For boards with electrodes located at centre width and centre length, this assumption is accurate enough even without sealed short edges. For the glulam beams, two-dimensional simulations were performed to evaluate the difference between a one- and two-dimensional model. For the latter, two simulations were performed, one assuming no transport over glue lines and the other assuming zero influence of glue lines. In both cases, the difference in moisture variations at the measuring points in question (10 mm from the top face, centre width, and surface) was very low, and therefore the final simulations were performed in a single dimension. The gravimetric measurements were made on specimens with sealed short edges, making a one-dimensional model analogous to the two-dimensional case. In this case (Lund C), zero flux was assumed through the back face, since it was sealed.

3. RESULTS AND DISCUSSION

This section provides an overview of the results (section 3.1) followed by a more in-depth analysis focusing on the influence of rain (section 3.2) and a discussion on possible measurement error, with emphasis on those stemming from the indirect nature of resistance-based moisture measurements (section 3.3). The section ends with ideas for future model improvement.

3.1 Moisture content

Fig. 3 shows the three datasets from Lund together with the simulated data. The comparison in the wood core (approximately 10 mm from the exposed surface or gravimetric) are shown in the bottom row of subfigures, and the corresponding comparison of surface moisture are shown in the upper row. In general, the model captures the main features of the experimental data, including seasonal but also sub-seasonal variations. From the measurements in the core, the lower bound of the model ($u_f = 60\%$) is more consistent with the experimental data. This is expected, as the surface moisture content during wetting was originally calibrated for sapwood. As a consequence, the model tends overestimate the effect of precipitation.

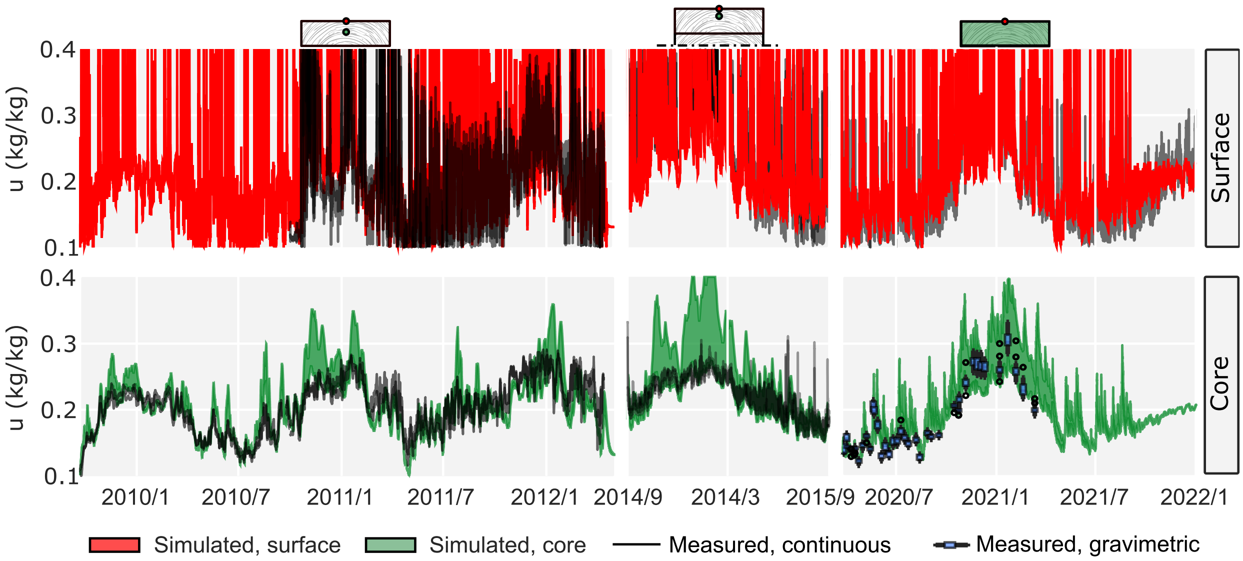

Figure 3. Measured and simulated moisture content variation for experiments carried out in Lund. The data is shown for wood surfaces (top, red = simulation, black = measured) and wood core (bottom, green = simulated, black = measured). The simulated values extend over the whole period even when measured values do not (top left and bottom right). The gravimetric measurements are shown with boxplots (whiskers extending to 25th and 75th percentiles) to indicate the range of variation.

Because resistance-type sensors have limited accuracy above the hygroscopic range, validating surface moisture content can be more challenging. Even so, Fig. 3 shows that both the seasonal variation and the general timing of moisture peaks were well captured in all three datasets. Previous studies have also shown consistent wetting durations in Lund A (Niklewski *et al.* 2016) and Lund C (Niklewski *et al.* 2023). A qualitative assessment of Lund B suggests a similar pattern. It should be noted that the design of the surface probes in Lund A differed from those used in the other two datasets. Rather than measuring the surface moisture content, they were intended to capture only the duration of surface wetting.

Fig. 4 shows the two datasets from Hannover together with the simulated data. Note that the x-axis scale and y-axis range remain consistent across all datasets from both locations to facilitate direct comparisons. Also in this case, the model captures the seasonal and sub-seasonal variations with reasonable accuracy. However, a few notable discrepancies are evident, including the first winter (a), a short period in the summer of 2013 (b) and a longer period during the summer of 2014 (c). In all these cases, the model overestimates the moisture content. These overestimated peaks are, as previously explained, expected due to the nature of the model calibration. Nevertheless, the two longer periods of consistent discrepancy are more difficult to explain. The wood appears to stabilise at a moisture content that is quite low compared to the equilibrium moisture content derived from the weather data. This discrepancy could be due to a mismatch between the weather data (used as input) and the actual local conditions on the wood surface. Although speculative, such an effect might occur during periods with high solar radiation and low wind velocity, leading to reduced relative humidity at the heated wood surface. This would not, however, explain the discrepancy during the initial winter months.

The comparison between simulated and measured moisture content across the five datasets reveals several key insights into the performance of the numerical model. In general, the simulated moisture content in the core aligns well with the measured data in all cases, demonstrating the model’s ability to capture overall moisture trends. Nevertheless, deviations between model predictions and measurements were observed, particularly during colder months. The lower accuracy in these colder periods may be related to snow and condensation, which are not explicitly represented in the model. In a heated bucket-type rain gauge, precipitation is recorded immediately, but the actual absorption of water by the wood is both delayed (until melting) and prolonged (compared to a rain event).

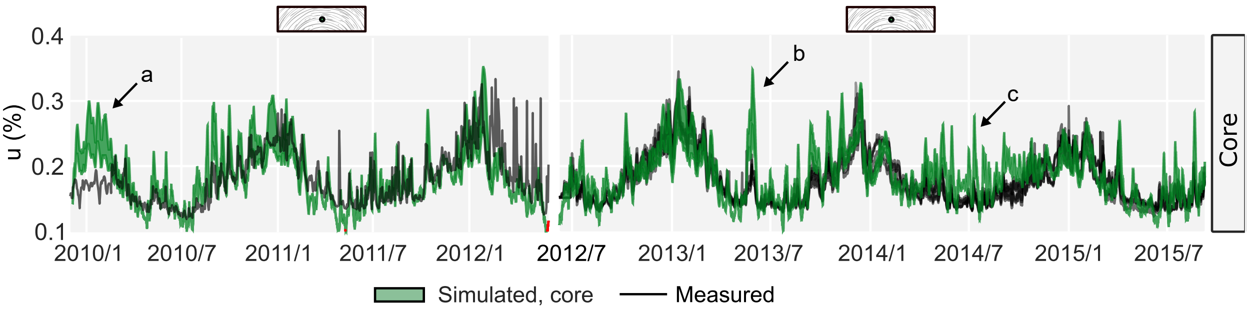

Figure 4. Measured (black) and simulated (green) variation in moisture content for experiments carried out in Hannover.

3.2 The effect of rain

Fluctuations in wood moisture content are primarily driven by changes in relative humidity and rainfall. Since periods of frequent rain often coincide with higher relative humidity, it can be challenging to distinguish the individual contributions of humidity and precipitation in outdoor conditions.

At the wood surface, moisture content responds quickly to ambient conditions. In the absence of rain, changes in surface moisture content are relatively slow and moderate. Precipitation causes a sharp, almost immediate increase in moisture content. This makes it relatively straightforward to assess model performance, on the surface, in the absence or presence of rain events. Deeper in the wood core, however, the response to rainfall can be delayed by several days and the corresponding peak is far less pronounced. Therefore, it is difficult to evaluate exactly how well the model considers the effect of precipitation on moisture transport deeper into the material.

One way to isolate the effect of precipitation is to include parallel measurements on sheltered specimens. If the sheltered and exposed boards experience the same ambient conditions (aside from exposure to rain), then the difference in their respective moisture contents can be attributed to precipitation. Two of the Lund experiments (A and B) included such measurements.

The average difference between sheltered and exposed specimens, Δu (kg/kg), is shown in Fig. 5. The overall trends resemble those seen in the comparisons of absolute moisture content, with greater discrepancies during winter than in summer. Over the summer, the additional moisture content due to precipitation remains at a relatively consistent level. A few things can be noted:

- The board experience more pronounced peaks in moisture content compared to the glulam beam. Conversely, the measurements on the beam indicated a more constant increase in moisture content caused by precipitation, which was caused by the buffering capacity of the larger wood volume.
- The simulated difference between sheltered and exposed boards tends to zero during longer periods without precipitation, whereas the measured values rarely reach zero. This could be caused by hysteresis.
- In the last winter (see 2012/1), Δu approached zero and even negative values were registered. During this period, both boards experienced very high and similar moisture content. It is unclear what happened during this period, but the test was terminated shortly after.

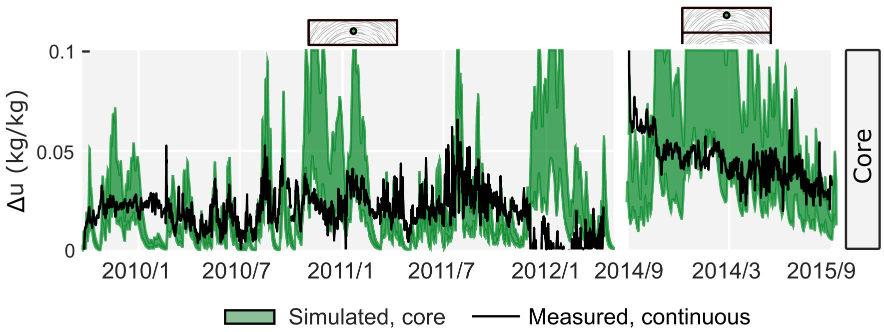

Figure 5. The difference in moisture content between the exposed specimens and sheltered specimens, isolating the effect of precipitation on moisture content.

3.3 Measurement accuracy

Resistance-type measurements have a limited range. Below 10% moisture content, the sensor must reliably measure electrical resistance in the giga-ohm range. Since the resistance of wood increases with decreasing temperature, the lower values are more difficult to measure during winter. In general, the lower limit is however not a major concern, because (1) the moisture content is rarely below 10% moisture content and (2) the moisture content tends to increase during winter (at low temperatures) due to increased relative humidity, as seen in Fig. 2-4. Resistance-based moisture sensors are relatively insensitive to small errors in resistance, since the calibration curve is logarithmic. However, the slope of the calibration curves declines rapidly at moisture contents above cell wall saturation. Consequently, subtle changes in resistance at such high moisture contents will have a strong effect on the measured moisture content. While the calibration curves used in the Hannover tests were calibrated for this range, the measured values should still be interpreted with some caution, as also stated by the authors (Brischke *et al.* 2017).

While the calibration curves used for the moisture sensors incorporate temperature compensation, their accuracy decreases when the wood temperature deviates significantly from the calibration temperature (typically 20 °C). In the datasets from Germany, the calibration curve was calibrated between 4 and 36 °C, whereas the Swedish datasets relied on a calibration curve produced by Hjort (1996). In cold conditions, the compensation may not fully correct for the effects of low temperatures, leading to potential under- or overestimation of moisture content.

In some datasets, wood temperature was assumed equal to the air temperature. This assumption introduces a systematic error, particularly on days with significant radiative heating or cooling. For example, during sunny days, wood temperatures may rise well above air temperatures during day (due to solar radiation) and decrease below the air temperature during night (due to radiative cooling), leading to artificially high diurnal fluctuations in measured moisture content. As noted in Niklewski *et al.* (2018b) the effect on the daily average moisture content is however small.

3.4 Future model development

In general, the model exhibited good agreement across all datasets, successfully capturing the dominant features of the measured moisture content variation. The consistent performance across datasets and different types of measurements indicates some robustness against smaller differences in local conditions between specimens, e.g. design of test setup or partial shelter from wind or solar radiation. As such, the model can be reliably used to provide valuable insights into the long-term behaviour of moisture in wood for durability applications.

Nevertheless, the greater discrepancies observed in winter suggest that further refinement of the model may improve accuracy, particularly in predicting seasonal variations. While this is not critical for durability applications, given that decay development tends to slow down or stop under low temperatures, future improvements may include:

- Incorporating more advanced temperature-dependent material properties.
- Simulating the wood surface temperature to account for shading effects, and radiative heating/cooling.
- Accounting for snow accumulation and sublimation effects.
- Refining boundary condition assumptions, and the time-of-wetness associated to rain effects under different conditions.

Overall, the findings support the reliability of the numerical model in predicting moisture content trends. However, it should be noted that the five datasets included in this study were still collected under relatively homogenous climate conditions, representing typical northern/central European climates. While the dataset includes a wide range of temperature conditions, additional validation should focus on other climates, such as tropical, very cold or very dry climates. By addressing these aspects, the predictive capability of the model and its application in durability applications can be improved.

In addition to the outdoor experiments presented in this paper, the same model has shown good agreement against laboratory studies (Fredriksson *et al.* 2016, Niklewski *et al.* 2018a). Notably, the study by Fredriksson *et al.* (2016) serves as an excellent benchmark as the moisture content was measured at multiple depths under controlled conditions, which is why the same data was used to calibrate the first application of the model (Niklewski *et al.* 2016).

3. CONCLUSIONS

The study tests the performance of a simple single-phase moisture prediction model for Norway spruce (*Picea abies*) when used with fixed parameters over several different datasets. The conclusions are summarised as follows:

- The single-phase diffusion-based model captured the dominant trends in moisture content across multiple outdoor exposure datasets, indicating some inherent robustness to small variations in exposure conditions and experimental design.
- Agreement between measured and simulated moisture content was generally strong when compared against different metrics, including moisture variation on the wood surface, in the core and globally (gravimetric measurements).
- Differences between exposed and sheltered specimens was more difficult to capture accurately, indicating that precipitation remains a dominant source of uncertainty.
- Consistent with previous studies, the model performance decrease during winter.
- Resistance-based sensors are extremely useful for providing continuous data but are also subject to a number of uncertainties and limitations in range. Gravimetric measurements offer the most reliable comparison in terms of absolute values, but continuous data is scarce.

Overall, the validated model offers a practical tool for service life estimation and decay risk assessment, supporting better design and maintenance decisions for timber structures exposed above ground. However, we identify two potential future needs to increase model reliability. First, the boundary conditions can be improved by modelling surface temperature and possibly effects stemming from snow. The former would affect the vapour pressure on the surface and thus the moisture flux. Second, validation efforts should be extended to include a broader range of climate types.

5. ACKNOWLEDGEMENTS

The work was funded by Formas (Swedish research council for sustainable development) [2021-02053]. Weather data was in part provided by the Institute of Meteorology and Climatology, Leibniz University Hannover.

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