Wood Science and Technology (2020) 54:769–786
https://doi.org/10.1007/s00226-020-01195-0

REVIEW

Evaluation of previous measurements of water vapor sorption in wood at multiple temperatures

Samuel L. Zelinka[1] · **Samuel V. Glass**[1] · **Emil Engelund Thybring**[2]

Received: 20 November 2019 / Published online: 8 June 2020

Abstract

Water vapor sorption is a fundamental physical property of wood and has numerous implications for the behavior of wood as a building material. As a result, water vapor sorption isotherms have been studied for over a century and are the topic of countless publications. Despite their importance and depth of study, there has not yet been a thorough review of these studies that can be used to guide readers to the highest quality sorption data. Sorption data acquired at multiple temperatures are frequently used for thermodynamic analysis or to validate sorption models. This review summarizes all known papers where water vapor sorption isotherms have been measured on wood at three or more temperatures and includes 27 studies published from 1930 to 2018. For each study, the quality of the data is evaluated from the experimental details listed in the publication. One of the essential details is the operational definition of equilibrium, often specified as a threshold for change in mass with time. Unfortunately, upon close examination of the methods, definitions of equilibrium in many cases were not specified or were lacking in stringency, which calls into question the accuracy of the data. In the end, only three of the 27 studies are recommended as being reliable for thermodynamic analysis or for validating sorption isotherm models.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00226-020-01195-0) contains supplementary material, which is available to authorized users.

✉ Emil Engelund Thybring
eet@ign.ku.dk

[1] Building and Fire Sciences, US Forest Service Forest Products Laboratory, Madison, WI, USA

[2] Department of Geosciences and Natural Resource Management, University of Copenhagen, Frederiksberg, Denmark

Introduction

The interaction between water and wood is fundamental for understanding the physical and mechanical properties of wood (Glass and Zelinka 2010; Siau 1995; Skaar 1988; Stamm 1964), and moisture greatly influences the resistance of wood to biodeterioration (Ringman et al. 2019). One of the key ways in which wood-water interactions are characterized is the sorption isotherm, which is the relationship between relative humidity (RH), also known as water activity (a_w), and equilibrium moisture content (EMC) of wood at constant temperature. While this area of research has recently seen increased experimental work with the advent of automated sorption balances, there have also been a number of recent works looking at theoretical aspects of the sorption isotherm.

Water vapor sorption in wood is typically understood in terms of sorption isotherm models. These models are often used to interpolate between measured values, to derive thermodynamic properties from the model fits to sorption data, and to develop a physical picture of the interactions between water molecules and wood polymers. Despite their widespread use, commonly used sorption isotherm models such as the Guggenheim-Anderson-de Boer or "GAB" (Anderson 1946; de Boer 1953; Guggenheim 1966), Hailwood and Horrobin (1946), and Dent (1977) isotherm models have been repeatedly shown to be inconsistent with measured wood thermodynamic properties such as enthalpy of sorption (Simpson 1980; Willems 2015; Zelinka et al. 2018). Therefore, new models are needed.

Sorption isotherm models require validation using measured data. For many models, data at multiple temperatures are required to test whether the model captures the correct temperature effects. In many cases, sorption isotherm models have been fit to the data presented in the Wood Handbook (Glass and Zelinka 2010). The Wood Handbook presents a table of EMC values at 5% RH increments and 10 °F (~5.6 °C) steps from below the freezing temperature of water (−1 °C) to well above the boiling point of water (132 °C). Therefore, it appears to present a robust data set for testing sorption isotherm models. However, Glass et al. (2014) investigated the historical origin and metamorphosis of this "dataset" and found that the actual measured values were never clearly documented, resulting in the unsolvable problem of knowing which tabulated values were determined from direct observations and which were interpolated or extrapolated. Furthermore, the lack of proper documentation of methodology and the absence of measurement error analysis means that the "dataset" must be regarded as unreliable for scientific purposes (despite its proven utility for many practical applications).

In light of the unreliability of the Wood Handbook "dataset", it makes sense to review the literature for other appropriate datasets that can be used for scientific purposes such as testing sorption isotherm models. In this review article, a substantial number of publications is examined that present water vapor sorption data for wood at three or more temperatures. The publications are evaluated in terms of the documentation of experimental details, the criteria for identifying equilibrium, the level of measurement uncertainty, and the level of control of the experimental conditions. From this review of 27 studies, three datasets were

found to have sufficient quality to be used for further development of sorption isotherm models.

Evaluation procedures and considerations

Literature search

Original literature sources were located using the online search engine Google Scholar (https://scholar.google.com) with search terms "wood", "sorption", "water", "moisture", "isotherm" in English, German, French, Swedish, and Danish. For each search, the resulting list of publications was screened for the number of temperatures as well as the type of sample material used. Only publications with three or more temperature levels below 100 °C performed on wood without treatment (e.g., modification, impregnation, degradation, etc.) were selected for further evaluation. Additionally, citations in found literature sources were used to discover publications not otherwise found with the online search engine. From the many studies examined, only 27 studies contained data for unmodified wood at three or more temperatures (Table 1).

The data of Stamm and Loughborough (1935) were explicitly excluded from this study. While these data are recognized as the basis of the EMC values in the Wood Handbook (Glass and Zelinka 2010) and have frequently been used to test sorption isotherm models (Avramidis 1989; Bratasz et al. 2012; Nakano 2006; Rawat and Khali 1998; Simpson 1980, 1971, 1973; Willems 2015, 2016, 2018), Glass et al. (2014) have shown that the data must be considered unreliable for scientific purposes, as discussed previously. In addition, several other publications were excluded from this evaluation for reasons related to data presentation. Greubel and Drewes (1987) presented a series of curves rather than discrete data points. The studies by Avramidis (1992) and Koumoutsakos and Avramidis (1999) reported derived thermodynamic quantities rather than the measured EMC and RH values. Finally, publications were excluded if the number of RH set points was four or less and the highest RH was less than 85%. The studies by Ahmet et al. (2000) and Ball et al. (2001) were excluded on this basis.

Sorption measurement methods

In this section, the experimental methods are briefly introduced before addressing issues of data quality in the following section. Further information on gravimetric techniques for measuring water vapor sorption in wood can be found in two recent reviews (Thybring et al. 2018, 2019). In this article, moisture content is expressed in units of grams of moisture per hectogram of dry material, i.e., g hg^{-1}, which is numerically equivalent to percentage moisture content (dry basis), i.e., % g g^{-1}.

One of the most common techniques is the saturated salt solution method, where RH is controlled by placing specimens above a saturated salt solution; the vapor pressure is therefore fixed (at a given temperature) by the Gibbs' Phase Rule as

Table 1 Overview of water vapor sorption datasets with three or more temperatures

Reference	Wood species[a]	Sample type	Temperature set points (°C)	Humidity control[b]	Ex/In situ Weighing
Bahar et al. (2017)	European oak, Algerian oak	Solid	50, 60, 70, 80	SSS	Ex situ
Bonoma and Simo Tagne (2005)	Ayous, ebony	No info	20, 30, 40, 50, 60	SSS	No info
Bonoma et al. (2007)	Moabi	No info	20, 30, 60	SSS	No info
Cao and Kamdem (2004)	Southern yellow pine	Solid	4, 15, 30, 40	SSS	Ex situ
Choong (1962, 1963)	Western fir	Solid	25, 32, 40	Vacuum apparatus	In situ
Djolani (1970, 1972)	Sugar maple	Solid	5, 21, 35, 50	SSS	In situ
Esteban et al. (2015)	Spanish fir	Solid	15, 35, 50	SSS	Ex situ[c]
Fan et al. (1999)	Sitka spruce, western hemlock, western red cedar, Douglas-fir, lodgepole pine	Solid	30, 45, 60	Conditioning chamber	No info
Fernández et al. (2014)	Obeche, limba	Solid	15, 35, 50	SSS	Ex situ[c]
Hedlin (1967)	Douglas-fir, spruce, poplar, bald-cypress, hard maple, Philippine mahogany, basswood, western red cedar, balsa, black walnut, tamarack, Sitka spruce	Solid	−16, −12, 21	Conditioning chamber	In situ
Hill et al. (2010)	Sitka spruce	Powder	14.2, 24.1, 33.5, 43.8	Automated sorption balance	In situ
Jakieła et al. (2008)	Lime wood	Solid	15, 24, 35	Automated vacuum balance	In situ
Jannot et al. (2006)	Afzelia, ebony, iroko, moabi, obeche	Solid	20, 30, 40, 50, 60	SSS	Ex situ
Kelsey (1957)	Klinki pine	Solid	10, 25, 40, 55	Vacuum apparatus	In situ
Koponen (1985)	Finnish birch, pine, spruce	No info	20, 40, 65	Conditioning chamber	No info
Krupińska et al. (2007)	Scots pine, Norway spruce, European white birch, willow	Solid	20, 50, 75	Automated sorption balance	In situ
Nkolo Meze'e et al. (2008	Bubinga	Solid	20, 38, 50, 60	SSS	Ex situ
Nsouandélé et al. (2018)	Azobé, ebony, iroko, sapelli	Solid	20, 30, 40, 50	SSS	Ex situ
Ouertani et al. (2011)	Palm wood	Solid	50, 60, 70	SSS	Ex situ
Ouertani et al. (2014)	Jack pine, palm wood	Solid	50, 60, 70, 80	SSS	Ex situ

Table 1 (continued)

Reference	Wood species[a]	Sample type	Temperature set points (°C)	Humidity control[b]	Ex/In situ Weighing
Pidgeon and Maass (1930)	White spruce, jack pine	Solid	12, 18, 23, 29, 33, 42	Vacuum apparatus	In situ
Simón et al. (2015)	Silver fir	Solid	15, 35, 50	SSS	Ex situ[c]
Simón et al. (2016)	Radiata pine, chestnut	Solid	15, 35, 50	SSS	Ex situ[c]
Themelin et al. (1997)	Basralocus, eucalypt	Solid	25, 50, 80	SSS	Ex situ[c]
Tveit (1966)	Balsa, abachi, spruce, pine, teak, doussie	Solid	5, 25, 45	SSS	In situ
Weichert (1963a, b)	Spruce, beech	Solid	25, 50, 75, 100	Vacuum apparatus	In situ
Yasuda et al. (1995)	Sitka spruce	Solid	10, 20, 30, 40, 50	SSS	Ex situ

[a]Common names; see Supplementary Material for scientific names and further details. [b]SSS: saturated salt solutions. [c]Specimens placed in bottles with stoppers closed during weighing

determined through the osmotic activity coefficient (Robinson and Stokes 1949; Stokes and Robinson 1948). A range of RH levels can be attained with various saturated salt solutions (Greenspan 1977). Specimens are typically removed at intervals and weighed on a laboratory balance although a few papers report in situ weighing methods. Equilibrium is typically defined as successive mass readings being identical or differing by less than a certain percentage of the previous measurement or a fixed value close to the resolution of the balance. In the end, the specimen dry mass is determined after drying in an oven, a vacuum oven, or over a desiccant. From each specimen mass in equilibrium with a specific RH, and the corresponding dry mass, the EMC at each RH condition is calculated.

A second technique is based on a conditioning chamber in which air is circulated. Humidity is controlled by using aqueous solutions, by mixing dry and vapor-saturated air, or by other means. Various types of conditioning chambers are further discussed by Thybring et al. (2019).

Automated continuous-flow sorption balances, also known as dynamic vapor sorption (DVS) analyzers, have been used extensively in wood research laboratories in the last decade. In this technique, a specimen (ca. 10–20 mg) is suspended from a microbalance in a temperature-controlled chamber. It is then exposed to a flow of carrier gas at a constant RH, which is generated from a mixture of dry and vapor-saturated streams of carrier gas whose flow rates are determined by mass flow controllers. The specimen mass is continuously monitored, and equilibrium is defined by a certain mass stability threshold or "stop criterion". Typically, stop criteria are expressed in terms of a change in specimen moisture content with respect to time (i.e., $\mathrm{d}M/\mathrm{d}t$) over a certain time window.

Another technique is the vacuum sorption apparatus. Early versions typically had specimens suspended from quartz helical springs inside glass tubes, with mass indicated (in situ) by elongation of the spring. Specimen dry mass was determined after evacuation of the apparatus with a vacuum pump. Valves or stopcocks allowed for isolation of the specimen from the vacuum pump and introduction of water vapor, with vapor pressure typically controlled either by an aqueous solution or by maintaining pure water at a temperature lower than the specimen to give saturated vapor at the desired temperature. Automated vacuum sorption balances use the same principle of controlling water vapor pressure in an otherwise evacuated system, but replace the quartz helix with an electronic microbalance and incorporate computer-automated data collection, similar to the DVS technique. It should be noted that the kinetics of sorption may be much more rapid in a vacuum apparatus than at atmospheric pressure; see Thybring et al. (2019) for further discussion.

Primary factors that affect data quality

The sorption isotherm is the relationship between EMC and RH at a given temperature. In principle, the quality of sorption data depends on the stringency of the operational definition of equilibrium, that is, how close to actual equilibrium the wood moisture content is when it is assumed to be at equilibrium based on fulfilling a certain criterion. Second, data quality depends on the inherent experimental

uncertainty in each measured value, including specimen mass, RH, and temperature. Third, the quality of sorption data depends on how stable the temperature and RH remain throughout the experiment. These factors are discussed in detail below.

Operational definition of equilibrium

For sorption experiments, equilibrium is identified in practice by maintaining constant temperature and RH conditions until the rate of change in wood moisture content with time becomes arbitrarily small. Operational definitions of equilibrium vary in two main respects: the criterion for mass change (or moisture content change), and the time interval over which the mass stability criterion is applied.

Measurements that involve manual mass readings are typically carried out until successive values, which are commonly taken at intervals of 24 h or more, are identical or differ by less than a fixed value or a certain percentage of the previous measurement. In order to compare the stringency of the operational definition of equilibrium between different studies, we calculate the rate of change in moisture content with respect to time, $\mathrm{d}M/\mathrm{d}t$. Our preferred set of units for comparison across studies is micrograms of moisture per gram of dry material per minute ($\mu g\ g^{-1}\ min^{-1}$). Conversion to these units from the commonly used change in percentage moisture content over 24 h is straightforward given that percentage moisture content (dry basis) is equivalent to grams of moisture per hectogram of dry material ($g\ hg^{-1}$). For example, a change of not more than 0.2 mg over 48 h for a specimen with dry mass of 1 g (Zelinka and Glass 2010) corresponds to 0.01 $g\ hg^{-1}\ day^{-1}$ or 0.07 $\mu g\ g^{-1}\ min^{-1}$. As an illustration of a percentage change in total mass, Esteban et al. (2015) considered equilibrium to have been attained when the change in specimen total mass was less than 0.1% over 24 h. Depending on the moisture content (which contributes to total mass), this criterion corresponds to $\mathrm{d}M/\mathrm{d}t$ values of 0.7 to 0.9 $\mu g\ g^{-1}\ min^{-1}$ (see Supplementary Material for calculations).

Studies using automated sorption balances for many years have commonly reported a criterion of $\mathrm{d}M/\mathrm{d}t \leq 20\ \mu g\ g^{-1}\ min^{-1}$ (0.002% MC min^{-1}) over a 10 min window. It was claimed that the moisture content when this criterion was met differed from the equilibrium moisture content at extended time by at most 0.1 $g\ hg^{-1}$ (Hill et al. 2009). However, this claim was not supported by any data. Moreover, this $\mathrm{d}M/\mathrm{d}t$ value is considerably larger than the values quoted above for manual mass readings, and the time window is considerably shorter. Glass et al. (2018) have shown, by comparing the moisture content when this criterion was met with a more stringent criterion of 2 µg change over 24 h (for 20 mg dry mass, $\mathrm{d}M/\mathrm{d}t \leq 0.07\ \mu g\ g^{-1}\ min^{-1}$), that the error associated with the original criterion is often greater than 1.0 $g\ hg^{-1}$ depending on the material and RH conditions. Even with a criterion of 10 $\mu g\ g^{-1}\ min^{-1}$ over a 10 min window, EMC errors range from 0.3 $g\ hg^{-1}$ to over 1 $g\ hg^{-1}$.

Measurement uncertainty

The primary measured quantities are specimen mass and the relative humidity and temperature of the system. Each measured value has an uncertainty associated with

calibration of the instrument with reference to a standard, and possible instrument repeatability effects such as drift and hysteresis. This uncertainty is distinct from the precision of the measurement. For example, an automated sorption balance may be able to resolve changes in mass with a precision of 0.1 µg, but its uncertainty (based on calibration, specimen loading, and drift) may be on the order of ± 1 µg to ± 10 µg. A potential benefit of high precision in temperature and RH measurement is that it may allow a control system to regulate the temperature and RH conditions with greater stability (assuming that sensor drift is negligible). This consideration is discussed in the following section.

EMC values are derived from specimen mass under various equilibrium conditions as well as the dry condition. Moisture content uncertainty depends on the mass measurement uncertainty relative to the specimen mass under both moist and dry conditions. As shown in the Supplementary Material, the moisture content uncertainty can be approximated as a factor of 1.5 times the ratio of mass uncertainty to dry mass. For example, an automated sorption balance with a mass uncertainty of ± 1 µg and a specimen dry mass of 20 mg yields a moisture content uncertainty of about ± 0.008 g hg^{-1}. For larger specimens conditioned with the saturated salt solution method and weighed using an electronic balance, the principle is the same. For instance, a mass uncertainty of ± 0.2 mg and a specimen dry mass of 1 g (Zelinka and Glass 2010) translates into a moisture content uncertainty of ± 0.03 g hg^{-1}. The mass uncertainty of the quartz helical spring technique depends on the spring constant of the quartz helix and the accuracy with which elongation can be measured. Specimen sizes and mass uncertainties vary widely in the literature; the Supplementary Material provides further information and an assessment for each publication.

Measurement uncertainty in RH values can also vary considerably depending on the type of sensor and the specific RH and temperature conditions under which the measurement is made. Uncertainty typically increases at high RH levels and at low and high temperatures. In many cases, equilibrium RH values for saturated salt solutions are based on the literature. In this case, Greenspan (1977), for example, reports uncertainties for each salt over a range of temperatures.

Temperature measurement uncertainty is generally a lesser concern than EMC and RH measurement uncertainty. Nevertheless, calibration of temperature sensors is important for scientific measurements.

Temperature and relative humidity stability

Temperature fluctuations may affect sorption measurements in two ways. The first is that the relationship between RH and EMC is temperature-dependent, and therefore, a change in temperature will affect the EMC of the material. The second and more important effect is that RH itself is a strong function of temperature, because the relative humidity is defined as the ratio of vapor pressure to saturated vapor pressure, and the saturated vapor pressure of water is a strong function of temperature.

For automated sorption balance (DVS) measurements, the temperature is quite stable. Glass et al. (2017) have shown that the temperature is typically within ± 0.025 °C from the set point. Furthermore, since the RH is controlled by mixing thermostatically controlled saturated and dry gas streams, the effect of

temperature on the RH control is negligible. Glass et al. (2017) reported that over a 2000 min measurement, the RH stayed within ± 0.05% RH of the setpoint of 95% RH.

The temperature stability in studies using a vacuum sorption apparatus has been reported between ± 0.002 °C (Weichert 1963a, b) and ± 0.05 °C (Kelsey 1957). RH fluctuations based on these values are calculated in the Supplementary Material and range from ± 0.01% RH to ± 0.3% RH.

For saturated salt solution measurements, the RH stability depends upon the temperature stability, i.e., the magnitude and rate of temperature fluctuations. For slow (reversible) temperature fluctuations, it is assumed that the equilibrium RH of the salt solution is maintained throughout the temperature fluctuation. This is the case when the kinetics of water evaporation/condensation and salt crystallization/solvation are fast enough to maintain equilibrium. In this case, the RH stability can be calculated from the temperature stability by taking the derivative of the equilibrium RH-temperature relationship. Greenspan (1977) provides a table of such data for many common salt solutions; these changes can result in a less than 0.4% RH change per Kelvin.

Much larger fluctuations in RH are possible if the temperature fluctuations are too fast for the salt solution to maintain equilibrium. In this case, the partial vapor pressure over a given salt solution can be assumed constant while the changing temperature causes the saturation vapor pressure to vary. A full mathematical treatment for these scenarios is given in the Supplementary Material. Example data for sodium chloride are presented in Fig. 1. The solid markers represent RH at the exact temperature. The lines on the graph represent the potential range of RH for two commonly reported temperature stability criteria: ± 0.5 °C and ± 0.1 °C. Note that at room temperature, rapid temperature oscillations within the tolerance of the conditioning chamber may cause RH fluctuations of up to 6% RH (3% RH above and below the equilibrium value).

Additionally, handling samples in the laboratory outside of the conditioning environment for ex situ weighing may produce significant uncertainty in the results, depending on how different the laboratory environment is from the conditioning

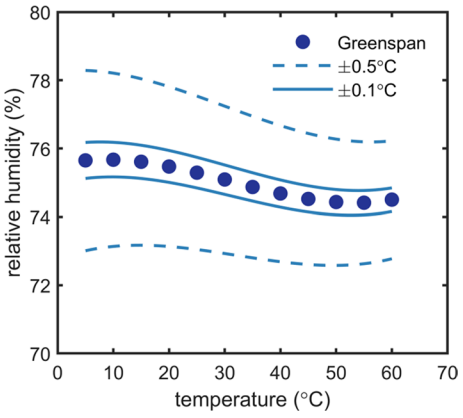

Fig. 1 Data (dots) and calculated values (lines) showing how temperature fluctuations can affect the relative humidity above a saturated sodium chloride solution for two commonly reported laboratory temperature controls

environment and how fast samples respond to a change in the surrounding environment. In general, in situ weighing of samples is to be preferred to limit these effects, but as seen in Table 1 many studies in literature have used ex situ weighing. Placing specimens in weighing bottles with ground glass stoppers likely reduces the disturbance in the conditioning environment, but does not eliminate it.

Sorption history

The EMC of wood does not only depend on external parameters such as relative humidity and temperature. It also depends on the internal moisture state of the wood prior to equilibrium, i.e., the sorption history. This phenomenon is known as sorption hysteresis, and can be seen as a difference in moisture content between equilibrium reached by absorption (moisture gain) and desorption (moisture loss) (Fredriksson and Thybring 2018; Pidgeon and Maass 1930). In this study, the general term "absorption" is used for describing the process of moisture gain in wood, instead of "adsorption" which is more common in the wood literature. This is in line with the definitions by the International Union of Pure and Applied Chemistry (IUPAC) which state that "absorption" refers to the uptake of one material by another, regardless of the mechanism, while "adsorption" specifically refers to uptake on surfaces/interfaces.

The effect of sorption hysteresis on equilibrium necessitates that the wood is brought to a well-defined moisture state before being exposed to given climatic conditions. For collecting absorption data, the dry state is predominantly used since the residual moisture content is minimal and closely similar (Hergt and Christensen 1965). For the desorption data reported in the literature, several different moisture states are taken as the starting point. A typical moisture state is that reached by absorption to 95% RH, while several studies use more humid vapor conditions as the starting point. However, none of these conditions are able to fully water-saturate the wood cell walls (Fredriksson and Thybring 2019). For collecting desorption data, the most well-defined initial moisture state is that obtained at full water-saturation of the wood, while starting from non-saturated conditions will result in more variable and complex sorption isotherms (Fredriksson and Thybring 2018).

Evaluation criteria

From the literature that was reviewed, each publication was thoroughly examined and 23 pieces of information analyzed. A full compilation for each study is presented in the Supplementary Material, ranging from information about wood species and number of RH set points to temperature stability and mass uncertainty. Rarely were all 23 details of the experimental method reported. Care was taken to estimate or calculate the missing parameters of importance based on the available information in the methods section of the papers. For instance, in the absence of information about RH stability this was estimated in the worst-case scenario of fast temperature fluctuations if information about temperature stability was available. Based on the compiled information about each study, they were then evaluated according to five

Table 2 Evaluation criteria

	Very good	Good	Fair	Poor
dM/dt at end of sorption (μg g^{-1} min^{-1})	$dM/dt \leq 0.1$	$0.1 < dM/dt \leq 1$	$1 < dM/dt \leq 2$	$dM/dt > 2$
Moisture content uncertainty, E_M (g hg^{-1})	$E_M \leq 0.01$	$0.01 < E_M \leq 0.15$	$0.15 < E_M \leq 0.5$	$E_M > 0.5$
Temperature stability, ΔT (°C)	$\Delta T \leq 0.01$	$0.01 < \Delta T \leq 0.1$	$0.1 < \Delta T \leq 0.5$	$\Delta T > 0.5$
Relative humidity stability, ΔH (% RH)	$\Delta H \leq 0.1$	$0.1 < \Delta H \leq 0.5$	$0.5 < \Delta H \leq 1$	$\Delta H > 1$
Replicates	> 3	3	2	1

criteria as listed in Table 2. The reported or estimated value of dM/dt at the end of each sorption step was used for assessing whether specimens were likely to have achieved equilibrium. The dM/dt criteria are the best assessment we have at present. The rate of approach to equilibrium is a complex topic and may depend on specimen size, geometry, and temperature. Further research is recommended (Thybring et al. 2019). Of the remaining factors, moisture content uncertainty (based on mass measurement uncertainty), temperature stability, and RH stability have been discussed previously. Finally, the number of replicates was evaluated. When multiple specimens are individually weighed in situ, this provides greater confidence in the mean value and useful information about variation. However, if all the replicates are weighed in aggregate, information about variation is lost. Furthermore, if specimens are weighed ex situ, repetition has little value, because all replicates may contain systematic error. To be considered reliable, high quality data, a rating of "good" or "very good" was required across the first four criteria as given in Table 2.

Results and discussion

An overview of the evaluations for each study is given in Table 3. The table is useful for quickly comparing the quality of different studies. To make the table easy to analyze, studies were rated as very good (vg), good, (g), fair (f), or poor (p) according to the criteria in Table 2, or having no information (n.i.) on which to base an evaluation. The ratings in Table 3 indicate that many studies did not specify important experimental details.

Only three studies achieved a rating of "good" or "very good" across the first four criteria in Table 3: Weichert (1963a, b), Hedlin (1967) and Djolani (1970, 1972). Note that for even two of these three, the number of replicates was not listed. However, no other studies had sufficient data quality, because they either had insufficient information, the definition of equilibrium was not sufficiently stringent, the moisture content uncertainty was too large, or the temperature and humidity stability were not sufficient. While all three studies include desorption data, only the measurements by Djolani are known to be initiated from the fully water-saturated state.

The data from Djolani, Hedlin and Weichert are replotted in Figs. 2, 3, and 4, except for one datapoint in Fig. 2 that is above 40 g hg^{-1} moisture content and therefore outside of the plot area; the data files used to generate these plots are included

Table 3 Overview of the quality of water vapor sorption data in wood at three or more temperatures presented in the literature. The rating criteria are listed in Table 2

Reference	d*M*/d*t* at end of sorption	Moisture content uncertainty	Temperature stability	RH stability	Replicates
Bahar et al. (2017)	g	f	p	p	n.i.
Bonoma and Simo Tagne (2005)	n.i.	n.i.	n.i.	n.i.	n.i.
Bonoma et al. (2007)	n.i.	n.i.	n.i.	n.i.	n.i.
Cao and Kamdem (2004)	vg	vg	p	p	g
Choong (1962, 1963)	n.i.	vg	g	n.i.	f
Djolani (1970, 1972)	g	vg	vg	vg	vg
Esteban et al. (2015)	g	f	g	f	vg
Fan et al. (1999)	vg	vg	p	f	vg
Fernández et al. (2014)	g	f	g	f	g
Hedlin (1967)	g	g	g	vg	n.i.
Hill et al. (2010)	p	n.i.	g	vg	n.i.
Jakieła et al. (2008)	p	n.i.	n.i.	n.i.	n.i.
Jannot et al. (2006)	g	f	n.i.	n.i.	p
Kelsey (1957)	f	g	g	g	f
Koponen (1985)	n.i.	n.i.	n.i.	n.i.	vg
Krupińska et al. (2007)	p	vg	n.i.	p	f
Nkolo Meze'e et al. (2008	g	f	n.i.	n.i.	n.i.
Nsouandélé et al. (2018)	n.i.	n.i.	n.i.	n.i.	n.i.
Ouertani et al. (2011)	g	f	p	p	n.i.
Ouertani et al. (2014)	g	f	p	p	n.i.
Pidgeon and Maass (1930)	n.i.	g	vg	vg	n.i.
Simón et al. (2015)	g	f	g	f	vg
Simón et al. (2016)	g	f	g	f	n.i.
Themelin et al. (1997)	n.i.	f	g	f	vg
Tveit (1966)	n.i.	n.i.	g	g	f
Weichert (1963a,b)	g	g	vg	vg	n.i.
Yasuda et al. (1995)	n.i.	vg	f	p	p

as electronic supplementary material. To improve the readability of Figs. 2, 3, and 4, the ABC sorption isotherm (Zelinka et al. 2018) has been fitted to the sorption data at each temperature. These data appear to be of high enough quality for testing sorption isotherm models. Although this review is limited to studies with sorption data at three or more temperature levels, the Hedlin data plotted in Fig. 4 only covers two temperatures. At the lowest temperature level in that study, the temperature control appears to be significantly poorer than the level stated by Hedlin (1967), see Supplementary Material. Therefore, Hedlin data measured at the lowest temperature have been excluded. It is again worth noting that the data of Weichert (1963a, b), Hedlin (1967) and Djolani (1970, 1972) represent a much better dataset for testing sorption isotherm models than the "dataset" in the Wood Handbook (Glass and Zelinka

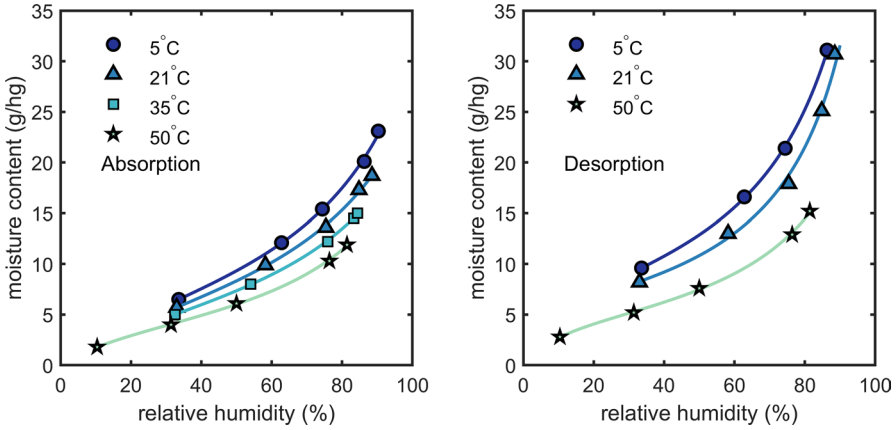

Fig. 2 Absorption (left) and desorption (right) data of Djolani (1970, 1972) collected on sugar maple at four different temperatures

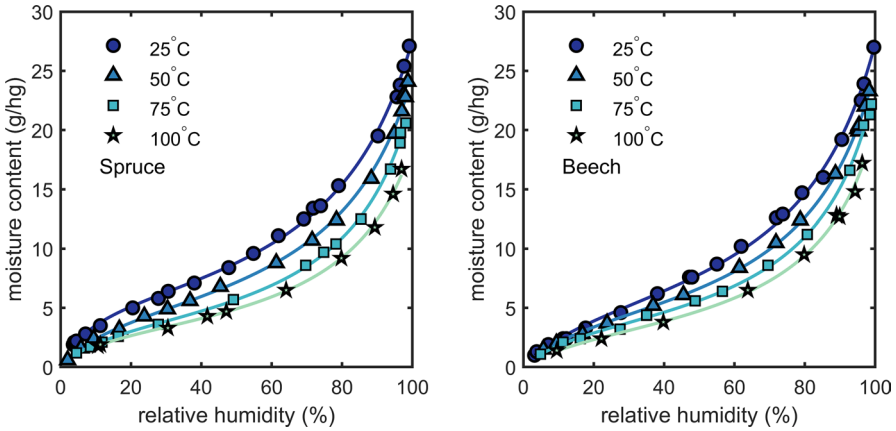

Fig. 3 Absorption data of Weichert (1963a, b) at four temperatures for spruce (left) and beech (right)

2010) for reasons discussed previously (Glass et al. 2014). In the absence of further quality sorption data at multiple temperatures, the data of Weichert (1963a, b), Hedlin (1967), and Djolani (1970, 1972) represent the highest quality data sets currently available in literature.

As a final note, it should be emphasized that it is important to list all relevant experimental parameters when publishing studies of water vapor sorption in wood. While the scientific method is based upon presenting enough information for a peer to replicate an experiment, in practice, very often shortcuts are taken when writing the "Materials and Methods" section. However, these unintentional omissions can affect the usefulness of the data. Table 4 presents the recommended minimum

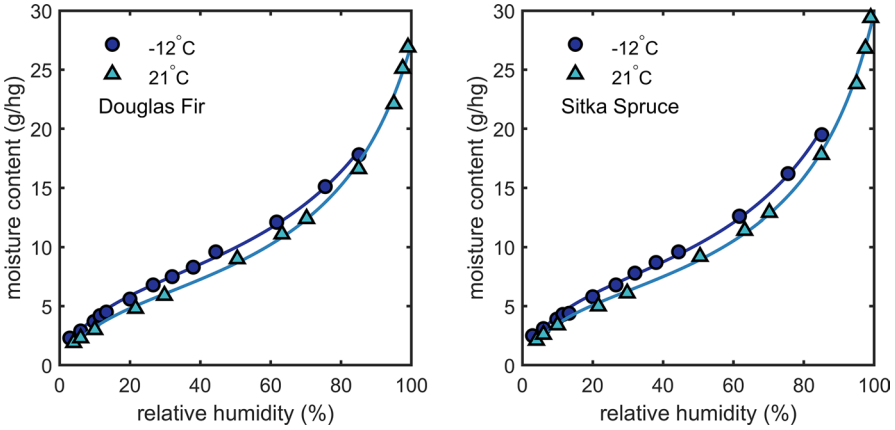

Fig. 4 Absorption data of Hedlin (1967) for Douglas fir series 1 (left) and Sitka spruce (right) at two of the three temperature levels in the study. See the text for further detail

Table 4 Recommended minimum amount of information to be specified when reporting sorption isotherm data

Information	Recommended level of detail
Basic specimen information	Wood species
	Specimen history
	Specimen dimensions and orientation
	Number of replicates
	Specimen dry mass
Drying protocol	Temperature
	Atmosphere (vacuum, air with desiccant, air)
	Mass stability criterion
	Duration
Sorption protocol	Initial moisture state before absorption and desorption
Mass measurement	Balance resolution and uncertainty
Equilibrium definition	Equilibrium criterion (mass change, period)
	Time to equilibrium
	Moisture content change (dM/dt) at the end of a sorption step
Temperature control	Method for regulating temperature
	Method for measuring temperature
	Measurement uncertainty
	Temperature set points
	Temperature stability
Humidity control	Method for regulating RH
	Method for measuring RH
	Measurement uncertainty
	RH set points
	RH stability

amount of information that should be reported with sorption measurements. It is hoped that this information will be listed in future water vapor sorption studies.

Conclusion

This paper reviewed the wood literature for studies that presented water vapor sorption isotherm data of wood without treatment (e.g., modification, impregnation, degradation, etc.) at three or more temperatures. Twenty-seven papers found by a thorough literature search met this criterion. The following conclusions are drawn from the evaluation:

- Too few papers report sufficient experimental details to evaluate the quality of the measurements. Future work must focus on ensuring the experimental methods are presented with enough detail so other researchers can evaluate the quality of the data and potentially repeat the experiments.
- The Wood Handbook "dataset" for equilibrium moisture content in wood should never be used for testing sorption isotherm models.
- Three of the 27 studies examined have sufficient data quality for testing and evaluating sorption isotherm models. These data have been re-plotted in this study and included in the Supplementary Material for future development of sorption theories about wood.

Acknowledgments The authors thank Roger Hernández and Claudia Cáceres at Université Laval, QC, Canada, and Leandro Passarini, Collège Communautaire Du Nouveau-Brunswick, NB, Canada, for details about the Djolani studies; Stavros Avramidis at University of British Columbia, BC, Canada, for details about the Fan et al. study; Jinzhen Cao at Beijing Forestry University, China, for details about the Cao and Kamdem study; Klaus Richter and Tanja Greisinger, TU Munich, Germany, for details about the Weichert study as well as for providing a copy of Weichert's thesis; and Roman Kozłowski at Polish Academy of Sciences, Kraków, Poland, for details about the Jakieła et al. study.

Funding Funding was provided by the US Forest Service and the University of Copenhagen.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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