Wetting and Drying Performance and On-site Moisture Protection of Nail-Laminated Timber Assemblies

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By:

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SUMMARY

In recent years nail-laminated timber (NLT) has been increasingly used in wood construction including both heavy timber non-residential buildings (e.g., floors, roofs) and light wood-frame residential buildings (e.g., elevator shafts). Such built-up assemblies, however, tend to have high wetting and low drying potential and are susceptible to moisture-related issues during the construction. A test was started in November 2014 to evaluate the wetting and drying performance of NLT, primarily following the protocols developed in a previous study on assessing the drying performance of roof assemblies (Wang 2014). A group of NLT assemblies, with variations in installing plywood sheathing and a protective membrane on the top, were exposed outdoors in Vancouver to assess the moisture protection provided by the sheathing or the membrane. In addition, two groups of specimens were put into an accelerated laboratory test of severe wetting through controlled spray of water, followed by drying in a shed, with or without heating as a purposely-created drying force. One plywood and two CLT specimens were included as reference specimens. Resistance-based moisture pin sensors were installed to assess the level of protection provided by sheathing or membrane during wetting, and the subsequent drying performance.

This study confirms that, without protection, water (e.g., rain) will penetrate and get trapped in NLT easily. Severe wetting will lead to elevated moisture content, approaching or exceeding 30%, in the central area (i.e., the core of a NLT member) and may require a long time (e.g., months) for drying. On a job site resistance-based moisture meters with long pins (probes) may be used to measure the moisture content in the central area, which will dry the slowest once wetted. Wetted NLT should always be dried before further assembly or enclosure, which further reduces the drying rate. Space heating is confirmed to be able to dry plywood, a thin panel even under reversed temperature differential conditions. It took about six weeks for severely wetted plywood, covered with an impermeable membrane on the top and with heating provided underneath, to reach moisture content of around 20% in the winter season. However, space heating is much less effective in drying NLT because they are large built-up members. But blowing hot air may be the most practical solution to dry NLT once severe wetting occurs at a construction site.

The best practice when working with NLT is to avoid wetting. On-site protection can be provided using the following measures, which are in order of increased level of protection, depending on weather conditions, risk and potential consequences of wetting, and costs of protection measures.

1. Pre-installing the sheathing (plywood used in this study) can provide a low level of protection to the NLT below. The joints between the sheathing panels should be immediately sealed (e.g. with tuck tape) upon installation to prevent localized moisture entrapment in the NLT. The areas that require on-site installation of the sheathing should be kept to a minimum and immediately protected after installation. Note the sheathing is also sensitive to wetting and should ideally be pre-protected using a membrane or coating, if possible.

2. Pre-installing a vapour-permeable membrane as a temporary protection measure when more advanced methods are not possible. The membrane may be pre-installed above NLT in the factory if the structural sheathing has to be installed at the site. The Grade D building paper and the permeable

plastic membrane (a type of housewrap) assessed in this study did not fully stop water penetration when they were laid over horizontal surfaces; however, the overall wetting was reduced.

3. Pre-installing a vapour-impermeable membrane, such as the permanent roofing membrane as a protective membrane for a roof structure. All the joints should be immediately sealed upon installation to prevent water penetration. However, installing an impermeable membrane on a wet assembly would eliminate moisture dissipation and must be avoided. Installing any material with low vapour permeance on wood deserves extra caution due to the greatly reduced drying ability. Installing a vapour-impermeable membrane will not be practical for structures, such as floors and elevator shafts that do not require an impermeable membrane in the final assembly. Temporary protection measures may be provided by installing a vapour permeable membrane.

4. Installing a temporary roof/shelter is the most effective and reliable on-site protection measure.

These similar protection measures are applicable to CLT and other mass timber systems.

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1   OBJECTIVES

- To assess the wetting and drying performance of a range of nail-laminated timber (NLT) assemblies under outdoor exposure and accelerated laboratory test conditions

- To investigate the level of on-site moisture protection that can be provided by sheathing (e.g., plywood) or a sheathing membrane

- To assess effectiveness of space heating on drying wetted NLT assemblies

- To help develop practical solutions to moisture protection of NLT during construction

2   INTRODUCTION

In recent years built-up assemblies, such as NLT, have been increasingly used in various wood buildings (StructureCraft 2015). They offer many advantages compared to traditional wood products, such as dimension lumber and solid-sawn timbers, particularly where large spans are required. However, built-up assemblies tend to have high wetting but low drying potential. The small gaps between nail laminated boards or sheathing panels (e.g., plywood, OSB) are susceptible to trapping moisture during installation in wet weather. The need for on-site moisture protection is recognized by the construction industry and practical solutions are demanded to better protecting NLT during construction and to improving the drying performance once wetting occurs (StructureCraft 2015; WoodWorks 2015). This study aimed to assess the wetting and drying behaviour of a range of NLT assemblies with variations in installing plywood sheathing and a protective membrane on the top. The specimens were tested under outdoor exposure conditions; or subjected to accelerated laboratory wetting and subsequent drying in a shed, with or without heating as a drying force. Resistance-based moisture pin sensors (about 180 sensors in total) were installed in the test assemblies to assess the level of protection provided by sheathing or a sheathing membrane during wetting, and the subsequent drying performance. General information about wetting and drying potentials of different wood products/assemblies and potential consequences of wetting can be found in relevant publications (Wang 2016a; 2016b).

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4   MATERIALS AND METHODS

4.1   Materials and Tests Setup

NLT assemblies, 14 in total, together with one plywood and two CLT reference specimens, were tested in the first phase of this study (Table 1). The NLT specimens (called "beam" when there is no plywood sheathing on the top) were built in the laboratory to simulate floor or roof decks. Each beam consisted of six boards of nominal 2 in. × 8 in. (38 mm × 180 mm) Douglas-fir dimensional lumber, being 900 mm long. The nailing of lamination generally followed the Clause 9.23.8.3 (7): Built-up Wood Beams, in the National Building Code of Canada (NRC 2005). Other nailing patterns were not investigated in anticipation that the nailing would have minor effect on the moisture performance dealt with in this report.

Three groups of specimens were tested: Group 1 for outdoor exposure; Group 2 for laboratory wetting, followed by drying in a shed without any space heating; Group 3 for laboratory wetting, followed by drying with each assembly supported on a plywood box in the shed, simulating conditions with or without space heating. Groups 1 and 2 aimed to assess the potential protection provided by the sheathing or the membrane installed above each beam during wetting as well as their effect on drying rates, and Group 3 focused on investigating the effect of space heating on the drying rates. The central parts along the length of the two middle boards of each beam were chosen for measuring MC to reduce edge effects. This study generally aimed to assess the one-dimensional wetting and drying behaviour across the depth of each specimen.

All beams except the NLT controls (i.e., N1 and S1) were covered with plywood sheathing, 19 mm in thickness. In assemblies N3 and S3, the sheathing had a butt joint in the middle to simulate a small gap, about 5 mm between two pieces of square-edged (as opposed to T&G) plywood. In many cases of construction, NLT decks are prefabricated in a factory but at least part of the sheathing is installed at the site to meet structural requirements. In assemblies N4, N5, S4, S5, a layer of Grade D building paper (asphalt-treated kraft paper, HAL-TEX 30 MINUTE) was installed between the beam and the sheathing, or over the sheathing as a potential protection mechanism for controlling rain ingress. Building paper may have advantages for being a protective membrane since it will have a minimal effect on the drying rates due to its high vapour permeance. Compared to many plastic membranes, building paper also has a lower material cost and will not make the surface slippery to cause a safety hazard during construction. However, the level of on-site protection building paper or other membranes can provide needed to be assessed. In addition to the NLT assemblies, two 3-ply CLT panels, labelled as C1LT and C2LT, were used as reference specimens in Groups 1 and 2, respectively. They were made with Canadian S-P-F (Spruce-Pine-Fir) and had dimensions of 900 mm (length) × 250 mm (width) × 90 mm (thickness). Figure 1 shows a NLT assembly including the NLT beam and the plywood sheathing. In Group 3, a type of self-adhered impermeable membrane (Henry Company) was installed on specimens B1, B4 and B5 to simulate the effect of an impermeable membrane (e.g., roofing membranes) on the drying rates.

Table 1   Wetting and drying schemes and test assemblies

Label	Assembly
Group 1: Wetting and drying during outdoor exposure. Each specimen was instrumented and assembled before exposure. It was approximately run from March 1 to November 1, 2015 (and additional field exposure test was approximately from December 1, 2015 to February, 2016, see Section 4.4).	
N1	Basic Assembly (control): NLT beam, no sheathing
N2	Beam + plywood, one sheet of sheathing without joint
N3	Beam + plywood, with a butt joint between two pieces of sheathing in the middle of the assembly along the length
N4	Beam + plywood, one sheet without joint, with a layer of building paper stapled on the beam before installing plywood
N5	Beam + plywood, one sheet without joint, with a layer of building paper stapled on the plywood
C1LT	Reference 3-ply CLT panel
Group 2: Each specimen was instrumented, assembled, and then wetted by controlled spray of water in the laboratory, followed by drying on a shelf in the shed (approximately April 1-November 1, 2015).	
S1	Basic Assembly (control): NLT beam, no sheathing
S2	Beam + plywood, one sheet of sheathing without joint
S3	Beam + plywood, with a butt joint between two pieces of sheathing in the middle of the assembly along the length
S4	Beam + plywood, one sheet without joint, with a layer of building paper stapled on the beam before installing plywood
S5	Beam + plywood, one sheet without joint, with a layer of building paper stapled on the plywood
C2LT	Reference 3-ply CLT panel
Group 3: Each plywood and beam was instrumented, wetted through controlled spray of water in the laboratory and then assembled, followed by drying above a plywood box, creating a simulated interior space (approximately April 1-November 1, 2015).	
B1	Reference plywood, 900 mm long and 240 mm wide, edge sealed, covered with an impermeable membrane, with a heater inside the plywood box below
B2	Beam + plywood, no membrane above plywood, and no heating inside the plywood box below
B3	Beam + plywood, no membrane above the plywood, with a heater inside the plywood box below
B4	Beam + plywood, an impermeable membrane covering the plywood, and no heating inside the plywood box below
B5	Beam + plywood, an impermeable membrane covering the plywood, with a heater inside the plywood box below

Figure 1   A nail-laminated timber assembly being instrumented in the laboratory

4.2   Instrumentation

Resistance-based moisture pin sensors, with each pin coated except at the tip to measure moisture content (MC) at a specific depth, were installed in the boards and in the plywood sheathing of each NLT assembly to assess localized wetting and drying behaviour. See Appendix I for information about measuring wood MC using such a method. A detailed instrumentation plan including the location and label of each sensor installed in assembly B2 of Group 3 is illustrated in Figure 2 as an example. For Groups 1 and 2, the measurements focused on the beams, covering the areas immediately below the sheathing, in middle depth, and at the bottom. The top surface of each beam was anticipated to pick up moisture quickly during wetting, and the central locations were anticipated to trap moisture and be slow in drying. Seven moisture sensors, plus one temperature sensor, were installed in a NLT beam as a complete instrumentation package (see Figure 2). There were fewer sensors in the beams of assemblies N4, N5, S4, and S5 since building paper was installed for protection and less wetting was anticipated. The sensors were concentrated in the middle along the length of each NLT. Each moisture pin sensor was installed from the side of the beam by drilling a small horizontal hole through the laminated boards. Each hole was sealed using a waterproof sealant afterwards to avoid interference with moisture movement. Two moisture sensors were installed in the middle layer of the plywood sheathing of assemblies N2, N3, S2, and S3. Due to the cost constraints, a single temperature sensor installed at a central location of each beam was used to determine the temperature compensation factor for the MC readings from the entire assembly.

Relatively more sensors were used to instrument the beam and the plywood of each test assembly of Group 3 before the laboratory wetting (Figure 2, see Section 4.3 for more details). Each beam was instrumented with the package of seven moisture sensors and one temperature sensor. For each of the 5-ply plywood sheathing, moisture sensors, also in a total of seven, were installed in the middle and the two surface layers to detect MC changes at different locations during the drying process. The moisture sensors were inserted into the plywood from the bottom surface to avoid penetration in the top surface;

the ambient temperature measured right above the sheathing was used to determine the temperature compensation factor for these MC measurements.

For the two CLT reference specimens of Groups 1 and 2, six (one sensor was missing) and seven moisture sensors were inserted into C1LT and C2LT, respectively. They were installed into the central and the two surface boards, targeting the central location of each board as well as the edges of the central board. The distribution of sensors was similar to those in the plywood sheathing of Group 3 (Figure 2). See Figure 31 to Figure 33 for details. One central temperature sensor was used to calibrate the MC readings.

A total of 134 moisture pin sensors, 19 temperature sensors, and 19 data loggers were installed in these 17 test assemblies in the initial setup. Several data loggers were reused from an old study due to budget constraints of this project. Each sensor was connected individually using thin wires to a wireless data logger. For Groups 1, data loggers were installed prior to the outdoor exposure and data collection was started at the end of February, 2015. For Groups 2 and 3, data loggers were installed after the specimens were set up in the shed at the end of March, following the laboratory wetting procedure. MC readings from each beam were calibrated for Douglas-fir, and those from the plywood and the CLTs were calibrated for lodgepole pine. Note the data logging systems, particularly the reused devices and the data loggers used exterior, malfunctioned a few times during the test, causing loss of data as shown in the figures and a few moisture pin sensors also failed.

Figure 2   Sensors in central cross section of nail-laminated timber and plywood sheathing as installed in test assembly B2 of Group 3

Note: All sensors were moisture pin sensors except temperature sensors of B2LT and B2AT. Regarding the labels, "B2" indicates the specimen number, "L" means the sensor is in boards of NLT, "P" means it is in plywood, and the last number in each label indicates the location. The letters and numbers in each label are consistent among all specimens.

4.3   Wetting and Drying Conditions

Each specimen was oriented as a small deck during the wetting and drying processes. Efforts were made to ensure that moisture would primarily move (i.e., wetting or drying) only across the depth of each assembly. The four edges of each plywood panel were sealed by applying two-part epoxy before wetting to simulate larger panels and to minimize edge effects. The edges of each NLT beam, except for small areas used for installing sensors, and the interface with the sheathing above were all sealed using impermeable membranes and tapes (see Figure 3).

4.3.1   Outdoor Exposure

Test assemblies from Group 1 were placed on shelves exposed to exterior conditions, starting at the end of February, 2015 (Figure 3; see Section 4.4 for description about the additional field exposure test). See App-Figure 1 and App-Table 1 (Appendix II) for information on the number of days of rain and precipitation amounts. Rainfall mostly occurred in the spring, fall and winter with a total precipitation of about 1037 mm from March 2015 to January 2016. The summer turned out to be drier than normal, with little or no rain from May to August. An RH/T sensor (HOBO, EL-USB-2-LCD RH/TEMP data logger) was used to measure the ambient temperature and relative humidity (RH) under a test assembly, with the RH and temperature readings shown in App-Figure 2 (Appendix II). There

were large daily fluctuations in temperature and RH. With the temperatures changing from 0°C to about 30°C, the RH fluctuated approximately between 50% and 100%. The humidity was particularly high, often recording 100% in the winter. Note that the device is not able to accurately measure RHs above 90%.

Figure 3   Test assemblies under outdoor exposure at FPInnovations' Vancouver laboratory

4.3.2   Laboratory Testing

The assembled specimens of Group 2 and the individual beam and plywood of Group 3 were wetted under controlled spray of water in the laboratory to simulate a severe wetting scenario caused by rain at a construction site. They were placed on shelves under spray nozzles in a facility at FPInnovations Vancouver laboratory (Figure 4). At a temperature of 20°C, the RH was controlled at about 90% to prevent drying from wetted specimens. The wetting procedure included hourly spray of water for approximately 18 days[1], with each spray lasting 5 seconds. It was estimated that about 80 litres of water in total was sprayed on each specimen, roughly equivalent to a rainfall of about 350 mm.

Group 2 was used to simulate drying of a sheltered assembly during construction with built-in moisture. After wetting, the test assemblies were placed on shelves in the rear of a shed to assess the drying behaviour under sheltered ("open shed") conditions with little temperature differentials or other external drying forces (Figure 5). The shed was covered but open to the exterior on one side, without any space heating or mechanical ventilation. The specimens had no exposure to sunshine or rain. The RH and temperature measured by a HOBO are shown in App-Figure 3 (Appendix II). The temperatures varied from 10°C to about 25°C and the RH fluctuated from 50% to 90%. Compared to the exterior conditions, the ambient environment in the shed had fewer and lower fluctuation in temperature and RH, and was overall warmer and drier in the winter.

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[1] There was disruption in the water spray system during the wetting procedure. 18 days was the estimated days of spray.

Group 3 was used to assess the effects of an impermeable membrane or purposely-created temperature differentials on the drying behaviour. Each specimen was assembled after the laboratory wetting procedure and then installed above a plywood box, measuring 900 mm × 1200 mm × 1200 mm (height) and simulating a small interior space (Figure 6). The box was not sealed and would allow some air exchange between inside and outside. A small heater was placed in the box for specimens B1, B3, and B5 to create a target temperature of around 20°C in the winter and to thereby create temperature differentials across the test assembly. For test assemblies B1 and B5, which had an impermeable membrane installed on the plywood to prevent moisture evaporation from the top surface, the direction of temperature gradients in wintertime (towards the membrane) were opposite to the direction that moisture can dissipate from the assembly (towards the heated box). The RH and temperature readings from boxes B1, B3, and B5 were reasonably consistent based on the measurements using HOBOs, which were placed close to the test specimens above. App-Figure 4 (Appendix II) shows the readings measured from box 1 as an example. The temperatures ranged from 20°C to about 30°C, with the RH fluctuating within 40-50%. It appeared that the heated plywood boxes created relatively warm, dry, and stable environment for the drying test.

Figure 4   Nail-laminated timber specimens being wetted by controlled spray of water in the laboratory

Figure 5   Nailed-laminated timber assemblies undergoing drying in the shed after laboratory wetting

Figure 6   Nail-laminated timber assemblies undergoing drying above plywood boxes in the shed

4.4   Additional Outdoor Exposure

When the MC readings from the test assemblies of Group 2 were judged to have levelled-off after the dry summer, it was decided to reuse those test assemblies by modifying and moving them outdoors to expand the natural exposure test, starting approximately December 1, 2015 (Table 2). This additional field exposure primarily aimed to assess the potential moisture protection that can be provided by three types of membrane products: building paper, a vapour-permeable plastic membrane (a plastic housewrap, DuPont), and a vapour-impermeable self-adhesive membrane (Henry Company)[2]. The

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[2] The water resistance of a membrane product is typically tested using the old "boat" test method (ASTM D779, ASTM 2003) or the "hydrostatic head" method (AATCC 127, AATCC 2014) related to exterior wall applications (Butt 2005; Holladay 2011). The Canadian Construction Materials Centre (CCMC) developed a "water ponding" test (which was summarized in "Technical Guide for Sheathing, Membrane, Breather-Type", but the detailed reference was not found). When a membrane passes this test based on the guidelines developed by CCMC, it is able to resist water penetration for 2 hours in a depth of water of 25.4 mm. The vapour permeance of a material can be tested based on ASTM E96 (ASTM 2013).

impermeable membrane was installed on test assembly NS2 (with the original label of S2) to cover the plywood sheathing to simulate a roofing membrane. For assembly NS4 and NS5 (with the original label of S4 and S5, respectively), the original building paper was replaced with the permeable plastic membrane. The assembly NS1 (with the original label of S1) was simply moved outdoors without any change in the assembly or the instrumentation to serve as a new reference specimen. In addition, the old building paper in N4 and N5 was replaced with fresh building paper in order to be comparable with the fresh membrane installed on NS2, NS4, or NS5. For test specimens NS4, NS5, N4, and N5, two moisture sensors were added in each NLT beam to have more measuring locations and two sensors were installed in the top surface of the plywood to detect potential water leakage through the membrane (see Figure 7 for added sensors in assembly NS5). It is well known that impermeable self-adhesive membranes have the highest water resistance but the lowest vapour permeance among membrane products (Butt 2005; Holladay 2011).

Table 2   Modifications in test assemblies for additional outdoor exposure (starting December 1, 2015)

| New label	Old label	Changes in assembly or sensors
NS2	S2	An impermeable membrane was installed on the plywood. Two malfunctioning moisture sensors in NLT were replaced. Two moisture sensors were added in plywood to detect potential leakage through the membrane.
NS4	S4	A permeable plastic membrane was installed between plywood and NLT. Moisture sensors were added in the NLT to cover more locations. Two moisture sensors were added in plywood to detect potential leakage through the membrane.
NS5	S5	A permeable plastic membrane was installed on plywood. Moisture sensors were added in the NLT to cover more locations. Two moisture sensors were added in plywood to detect potential leakage through the membrane.
N4	N4	Fresh building paper replaced the old building paper between plywood and NLT. Moisture sensors were added in the NLT to cover more locations.
N5	N5	Fresh building paper replaced the old building paper on plywood. Moisture sensors were added in the NLT to cover more locations.
NS1	S1	No change. A reference specimen.
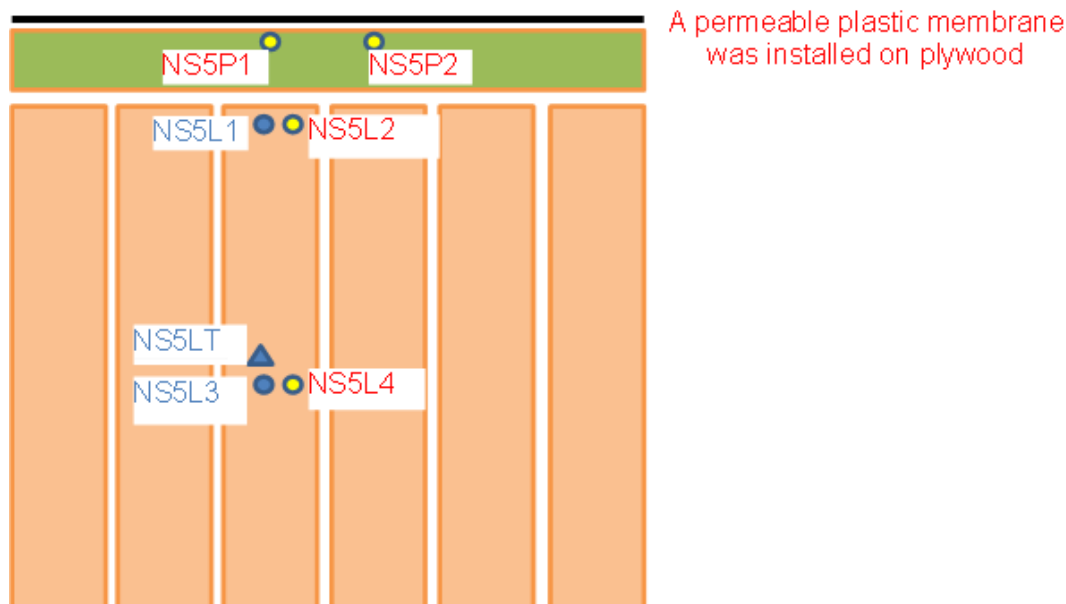
Figure 7   Sensors in central cross section of nail-laminated timber and plywood sheathing as installed in test assembly NS5 based on those in the original assembly S5

Note: Sensors with labels in red were added during modification for the additional outdoor exposure

5   RESULTS AND DISCUSSION

All MC charts below were created based on readings from the resistance-based sensors installed in the test assemblies without filtering or processing. The measurements were intended to provide general trends of MC changes in the boards or the plywood sheathing, with a primary interest in detecting potential risk. Overall the durability risk will be high when the MC is close to or above the fibre saturation point (i.e., 30%), and a MC of 26% was identified to be the critical MC for initiating decay when other conditions are favourable for fungal growth (Wang *et al.* 2010). However, the MC would have to stay at this level for several months for decay to initiate. See a relevant literature review for critical MCs which will likely lead to durability-related consequences, such as decay (Wang 2016a).

5.1   Wetting and Drying of NLT Assemblies during Outdoor Exposure

5.1.1   Outdoor Exposure

The outdoor exposure showed that there were large fluctuations in MC in the completely exposed NLT (i.e., N1), corresponding to rainfall events, when there was no sheathing or membrane on the top (Figure 8). The overall MCs were higher from April to May and from September to November, when it rained much more frequently and intensely than the summer months (App-Figure 1; App-Table 1). The sensors measuring the surface of NLT showed the highest MCs, approaching 30%; however, relatively high MCs around 25% were detected from the central locations. The latter would be more of a concern due to the low drying ability of the central areas. During the course of the dry summer, a few locations in the beam monitored by MC sensors, mostly in the surface, showed instantaneous increases in MC when it occasionally rained but the MC spikes also disappeared quickly. Overall the measurements

confirmed high moisture risk under wet weather conditions and relatively safe moisture conditions in a dry climate, when there is no moisture protection for NLT.

When a beam (i.e., N2) was covered with a sheet of plywood without a joint (a gap), the sheathing protected the NLT from wetting to a small degree (Figure 9). Water somehow still penetrated the plywood and reached the NLT below during intense rainy seasons, particularly in the fall (September-November). For example, there were only short-term spikes of MC in the NLT beam after rainfall events in April, which had a monthly precipitation of 51 mm within 11 rainy days. By comparison, October had 15 rainy days with a monthly precipitation of 113 mm. As a result the overall MC levels and durations of MC spikes were greatly increased. When there was a gap in the plywood sheathing (i.e., N3), not surprisingly the portion of NLT right below the gap was exposed to rain and experienced severe wetting (Figure 10). The wetting actually appeared to be more intense compared to the NLT without sheathing on the top (i.e., N1), probably due to the funnelling effect through the gap and the effects of the edges, which were more susceptible to wetting. This implies that all joints in sheathing should be immediately sealed upon installation to provide better protection to the NLT below to prevent localized moisture entrapment. Use of tongue-and-groove panels may have tighter joints and consequently reduce the level of water penetration through the joints. Figure 9 and Figure 10 also confirmed that plywood itself was absorptive of water and sensitive to wetting. Its middle layer, where moisture sensors were located, stayed wet under rainy conditions, with the MCs exceeding 30% in both N2 and N3. The plywood in N3, with a gap in the middle, appeared to be much wetter than that in N2. The two edges of the butt joint were not sealed against water absorption, which made them wet even after a small rain event in the summer. Overall the MC readings from plywood showed large fluctuations resulting from large temperature fluctuations during this study. The temperatures measured at a central location of the NLT beam did not reflect the real temperatures in the sheathing, particularly when the plywood was directly exposed to the sun. Fluctuating MC readings resulting from fluctuating temperature conditions in service had been reported (Winter *et al.* 2014); the impact of highly fluctuated temperatures on MC readings should be further investigated to improve MC measurements in field.

The test indicates that not only NLT decks, but also the sheathing above should be protected during construction in a wet climate, if possible. Protection should always be a higher priority over accelerating drying since most wood products/assemblies tend to have low drying rates. Only thin panels or small dimension elements can dry relatively fast when conditions allow (Wang 2014; Wang 2015). Large built-up assemblies, such as NLT would become more difficult to dry once wetting occurs. Moreover, the environment at a construction site in a cold and damp climate will rarely be favourable for drying. Regarding potential protection that can be provided by membrane-type products, the Grade D building paper tested appeared to provide additional protection to the NLT beam over that provided by the plywood alone (i.e., N2) (Figure 11). Sandwiching the building paper between the sheathing and NLT beam appeared to provide slightly better protection (i.e., in N4) compared to installing it above the sheathing (i.e., N5). This may also protect the membrane from damage that can be caused by wear and tear during construction. Installing a membrane on the top will also protect the plywood sheathing, but plywood alone dries relatively quickly after wetting (Wang 2014; 2015). Note a membrane product used as the water-resistive membrane of an exterior wall, such as building paper, plastic housewrap, and even self-adhesive membrane is not required to resist bulk water for a long time. Their major function is to shed water and to restrict moisture from ingress into a wall assembly. An exterior wall

must be designed and built to effectively exclude or remove bulk water by having rain deflection features (e.g., overhangs) and a good drainage capacity (e.g., through features such as a rainscreen wall cavity) (Hazleden and Morris 1999). This test confirms that building paper should not be expected to protect horizontal wood members for a long period of time during construction; although it may be used as a temporary protection mechanism. Detailed assessment is required for a specific project.
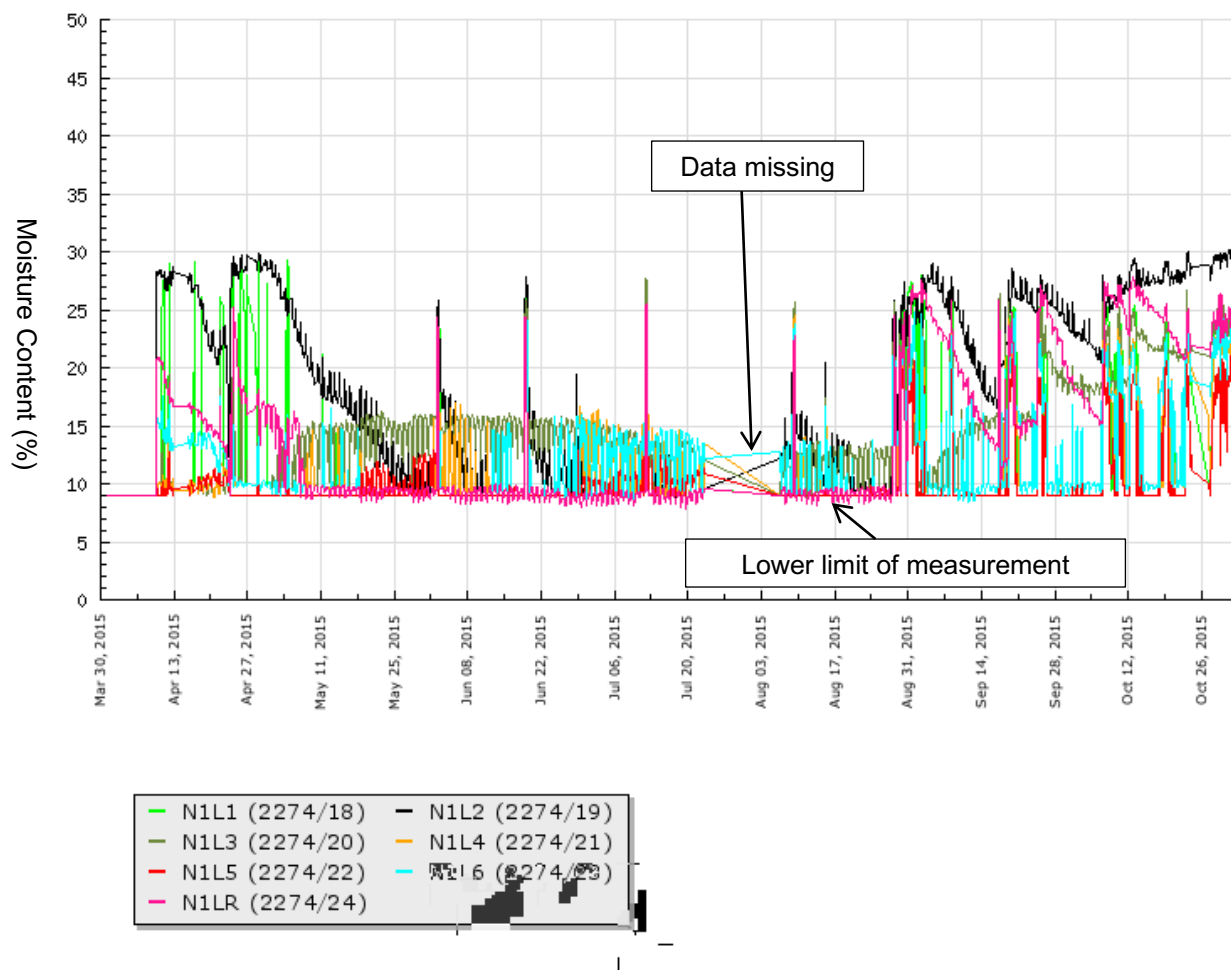

Figure 8   Moisture content readings from sensors installed in N1 beam without sheathing on top

Note: L—boards of NLT; number after "L": 1, 2—top surface; 3, 4, 5, 6—central; R—bottom
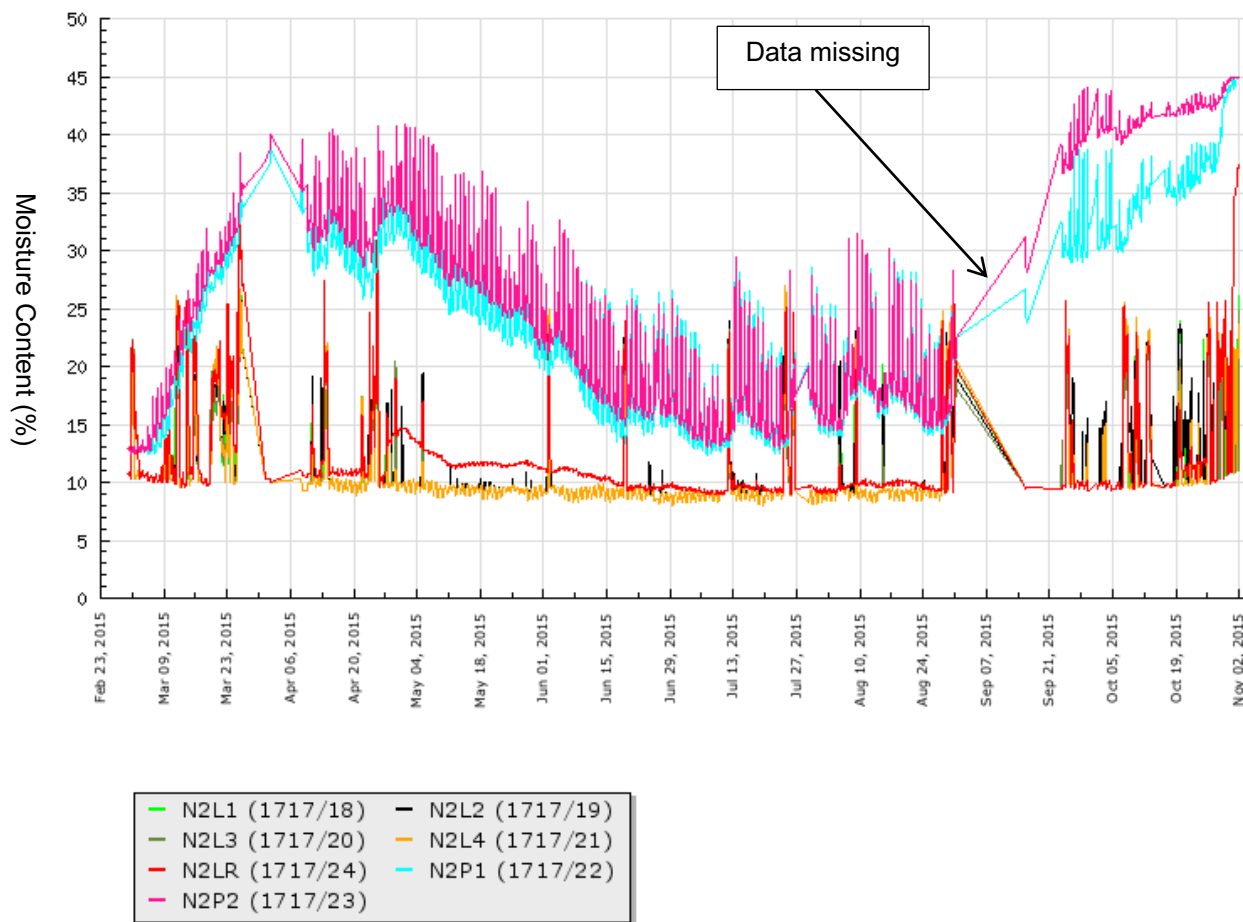
Figure 9   Moisture content readings from sensors installed in N2 beam and plywood sheathing

Note: L—boards of NLT; number after "L": 1, 2—top surface; 3, 4, 5, 6—central; R—bottom
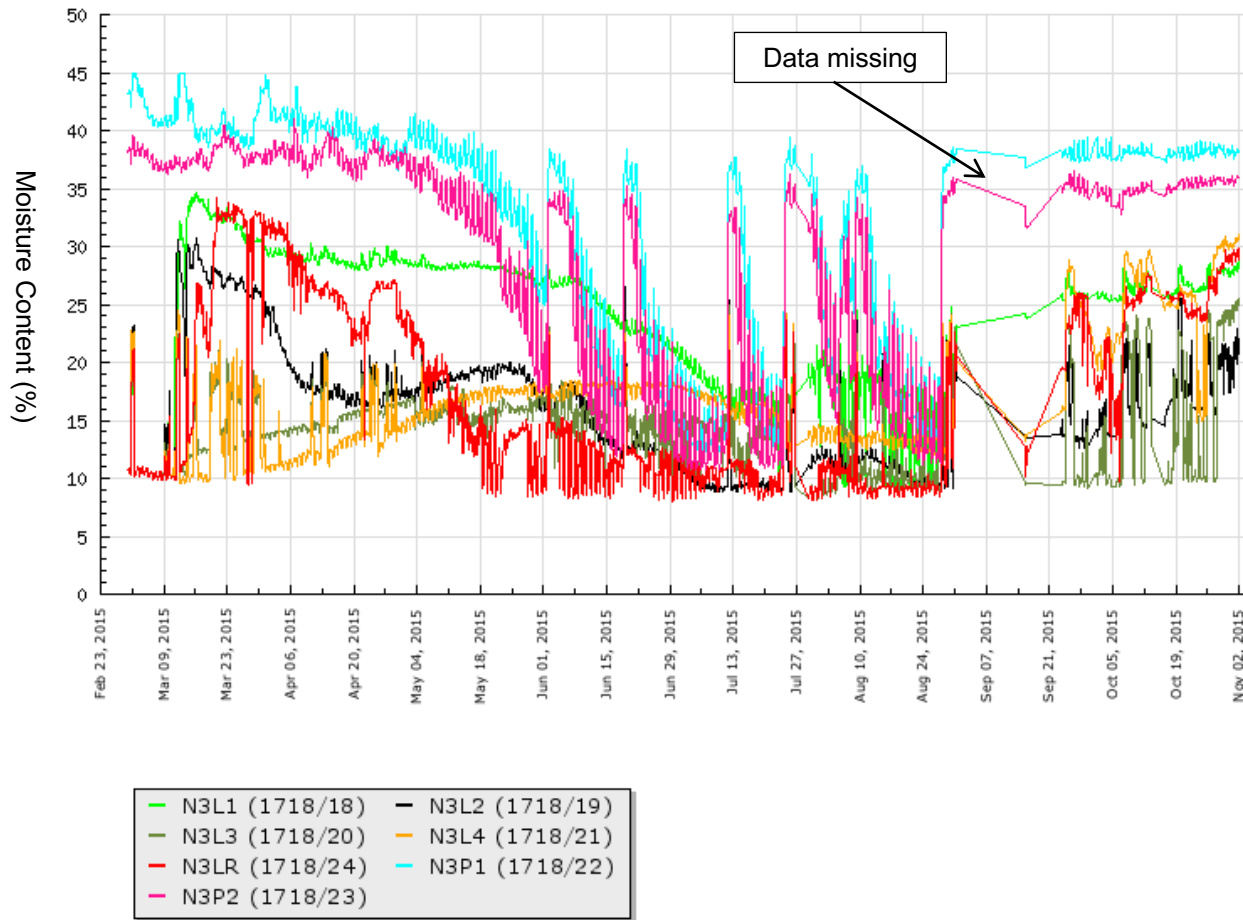P—plywood; P1, P2—middle layer of plywood

Figure 10   Moisture content readings from sensors installed in N3 beam and plywood sheathing with a gap in the sheathing

Note: L—boards of NLT; number after "L": 1, 2—top surface; 3, 4, 5, 6—central; R—bottom
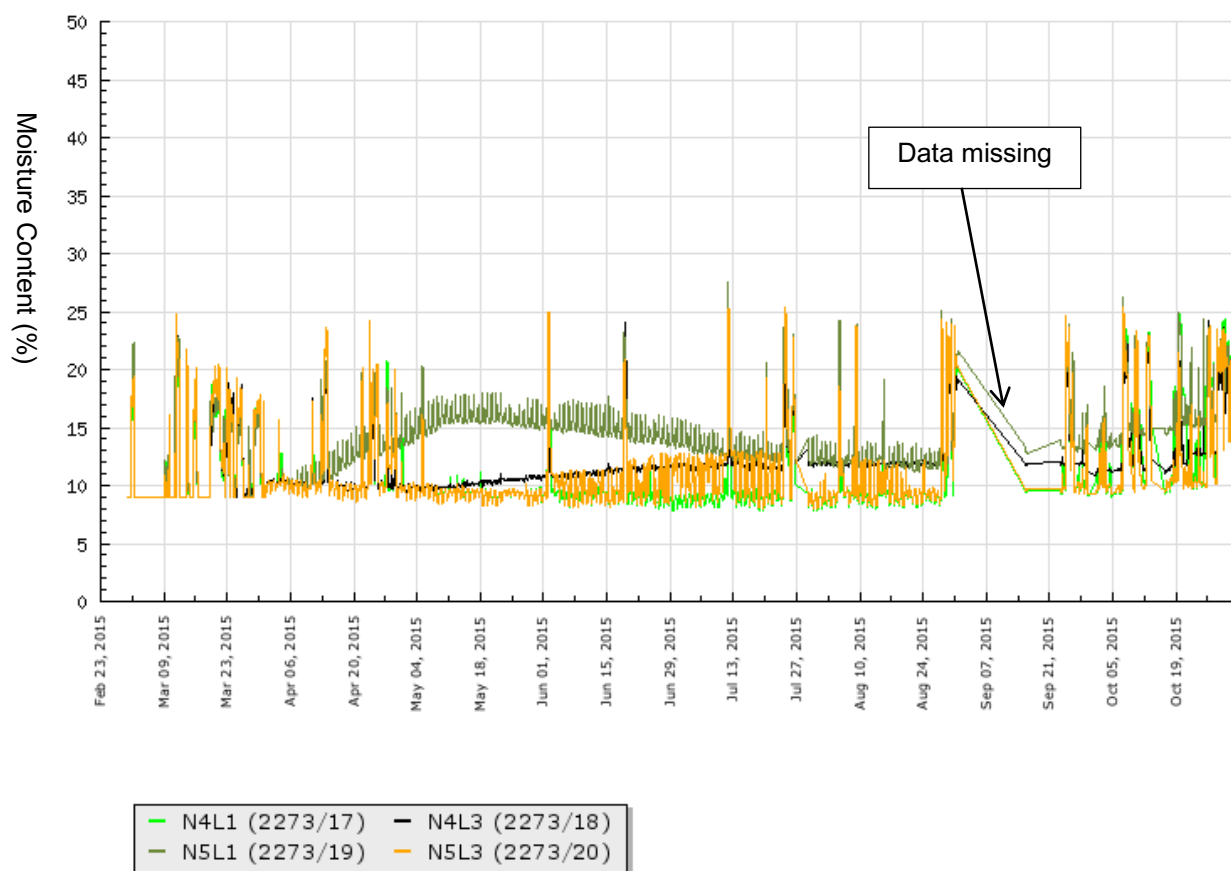P—plywood; P1, P2—middle layer of plywood

Figure 11   **Moisture content readings from sensors installed in N4 and N5 beams**

Note: L—boards of NLT; number after "L": 1—top surface; 3—central

5.1.2   *Additional Outdoor Exposure*

Data collection was not smooth and missing data occurred frequently during this approximately 2.5 month test. It appeared that the high humidity in the winter season added much stress, particularly on the reused data loggers. The collected data was therefore only used to show approximate trends. The reference NLT specimen (i.e., NS1, without plywood or membrane on the top) showed high MCs, not only in the top surface but also in the central areas (Figure 12), due to the intense rain after the specimen was set up in December. Regarding moisture protection provided by a membrane, it appeared that the impermeable membrane tested (assembly NS2) provided the best protection to the plywood and NLT below (Figure 13). MC at the two measurement locations in the top surface of the plywood stayed low during the exposure. By comparison, neither the building paper nor the vapour-permeable plastic membrane was able to completely stop moisture penetration, with the MC readings from the top surface of plywood around 35% throughout the exposure (Figure 14–Figure 17). The MC readings from the NLT below were roughly below 25%. The building paper appeared to be slightly more water-resistant than the plastic membrane. Integrating either of them between the beam and the plywood provided slightly better protection to the NLT compared to installing it above the sheathing.

In terms of implications of this test on practical on-site protection measures, heavy-duty roofing membranes are much more water-resistant and can provide better protection than the commonly seen vapour-permeable membranes used in exterior walls. Pre-installing a roofing membrane on a sheathed NLT can work well for a roof structure, when the protection work is coordinated with the roofer and other parties involved. Note that roof areas that are to be connected with adjacent NLT or plywood sheathing and cannot be pre-assembled due to structural reasons should be kept to a minimum. Those areas will require immediate protection once assembled at the site to prevent moisture ingress.

However, for other NLT applications such as floors and elevator shafts, where installing a roofing membrane or other impermeable membrane products becomes not practical, a light-duty membrane may be pre-installed as a temporary protection measure. Note rain may pass through the membrane, particularly when it is installed on a horizontal surface. The assemblies should therefore be sheltered by other parts of the building (e.g., roof) for more reliable protection as soon as the construction allows. Space heating may be needed to speed up drying if rainwater is found to have passed the protective membrane during construction. If the selected membrane is vapour-permeable, such as building paper, the membrane may be installed right above a NLT deck if the sheathing has to be installed at the site. This will provide slightly better protection to the NLT and also avoid potential damage to the membrane by wear and tear during construction. It should be pointed out that compared to relying on a protective membrane, the most effective and reliable on-site protection can be provided by a temporary roof/shelter by using impermeable plastic membranes (Wang 2016b). In a wet climate, planning the work around a temporary roof may become cost-effective as it brings certainty to protecting products/assemblies that are highly susceptible to entrapping moisture and tend to dry slowly after any wetting incident.
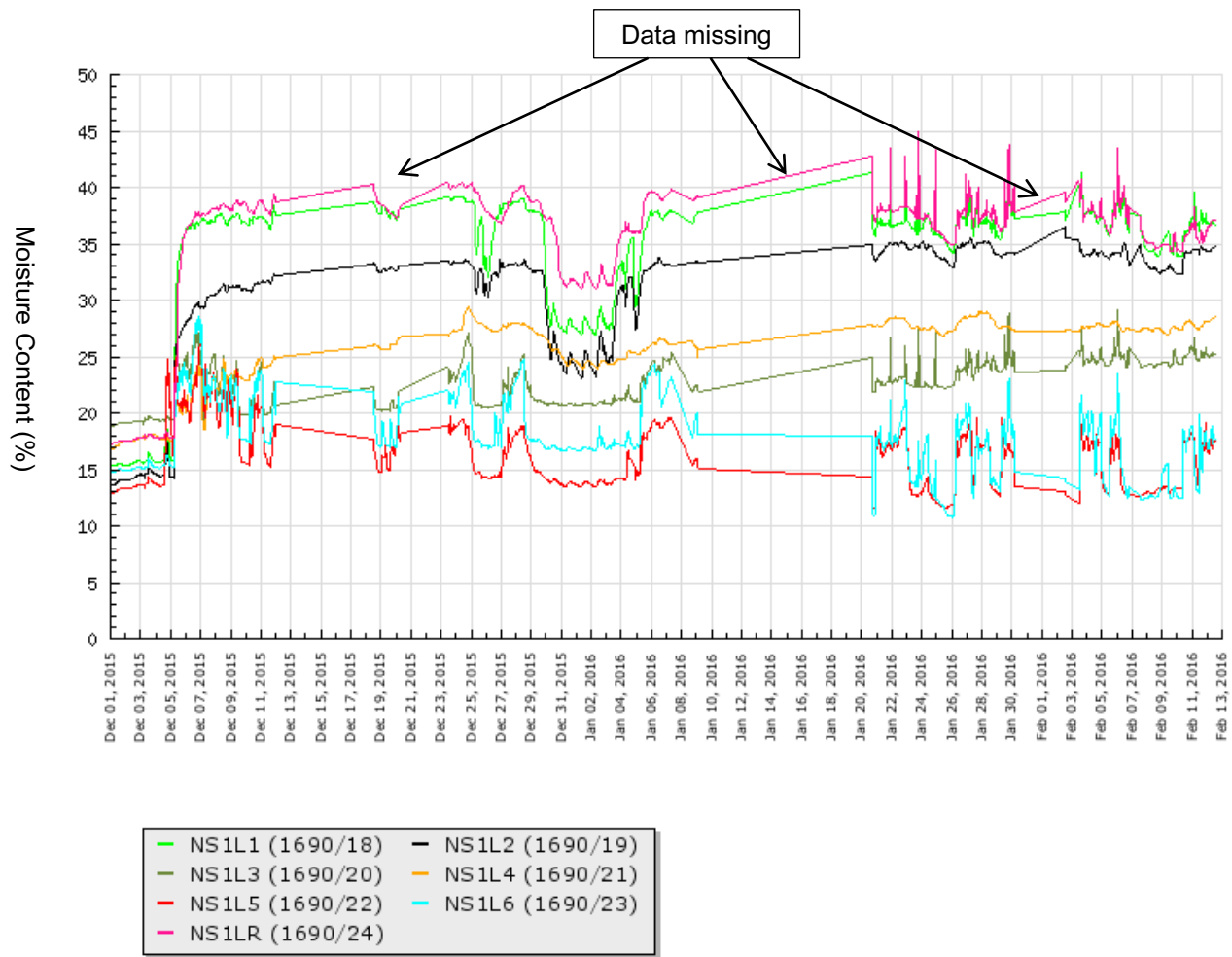
Figure 12   Moisture content readings from sensors Installed in NS1 beam without sheathing on top

Note: L—boards of NLT; number after "L": 1, 2—top surface; 3, 4, 5, 6—central; R—bottom

Figure 13 Moisture content readings from sensors installed in assembly NS2 with an impermeable membrane on the top

Note: L—boards of NLT; number after "L": 1, 2—top surface; 3, 4—central; R—bottom
P—plywood; P1, P2—top surface of plywood

Figure 14 Moisture content readings from sensors installed in assembly N4 with building paper between beam and plywood

Note: L—boards of NLT; number after "L": 1, 2—top surface; 3, 4—central

P—plywood; P1, P2—top surface of plywood

Figure 15   Moisture content readings from sensors installed in assembly N5 with building paper above plywood

Note: L—boards of NLT; number after "L": 1, 2—top surface; 3, 4—central

P—plywood; P1, P2—top surface of plywood

Figure 16   Moisture content readings from sensors installed in assembly NS4 with a permeable membrane between beam and plywood

Note: L—boards of NLT; number after "L": 1, 2—top surface; 3, 4—central
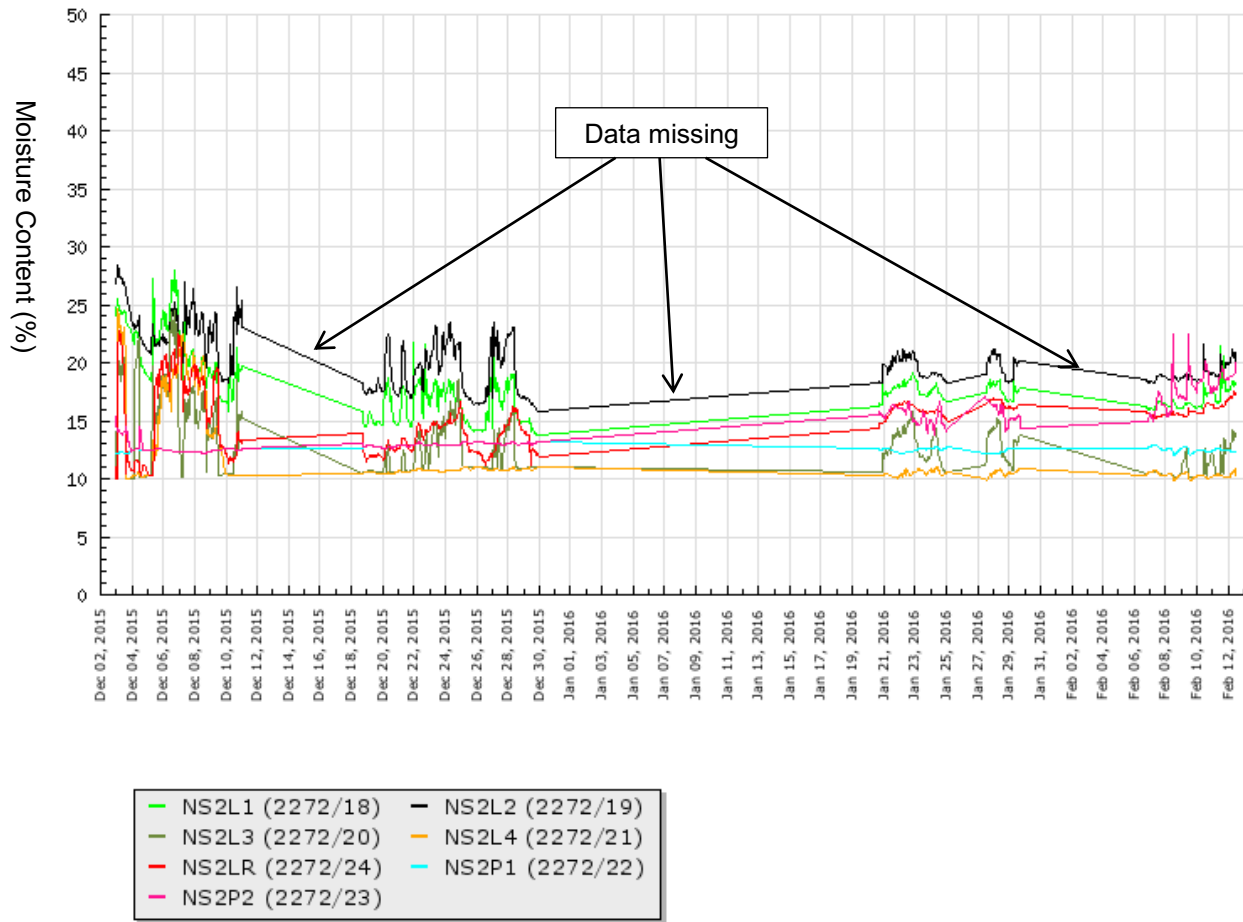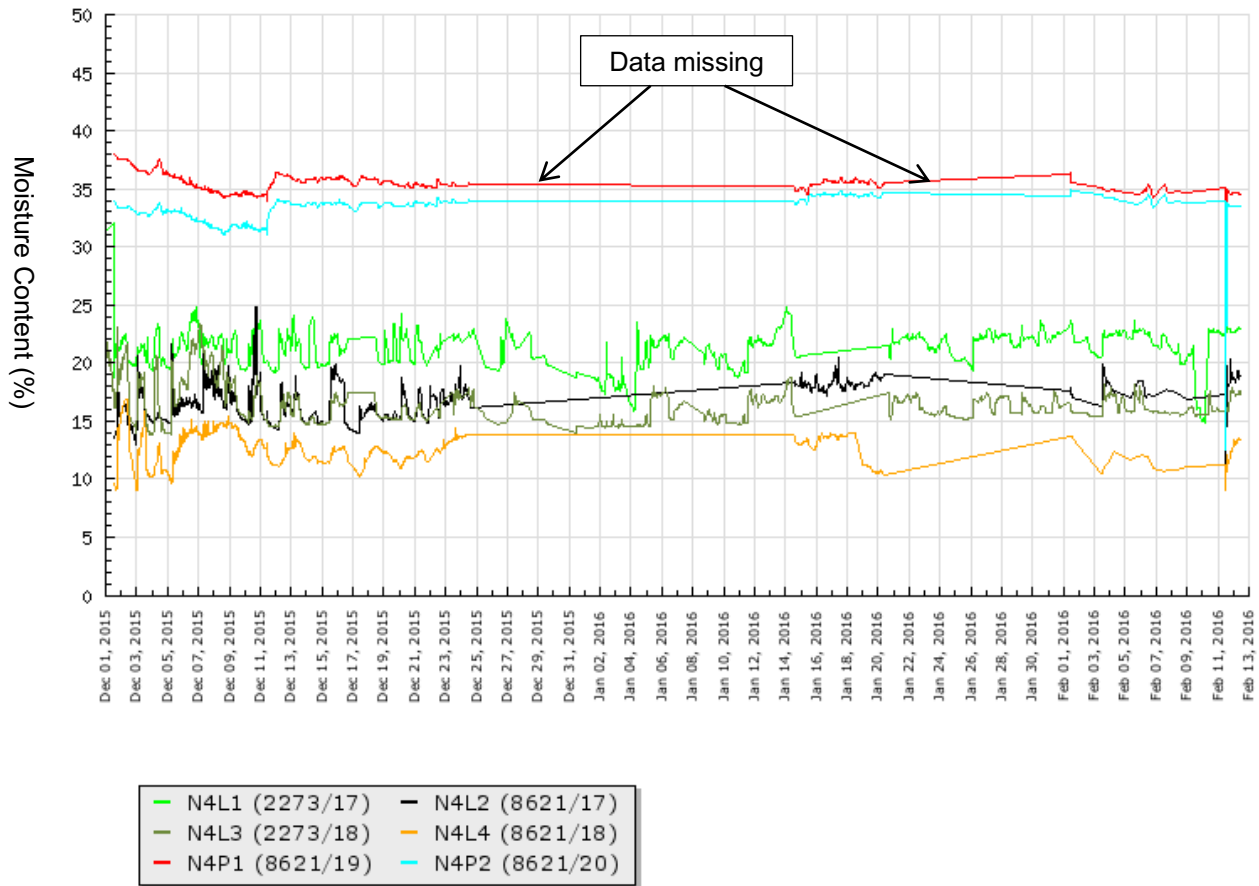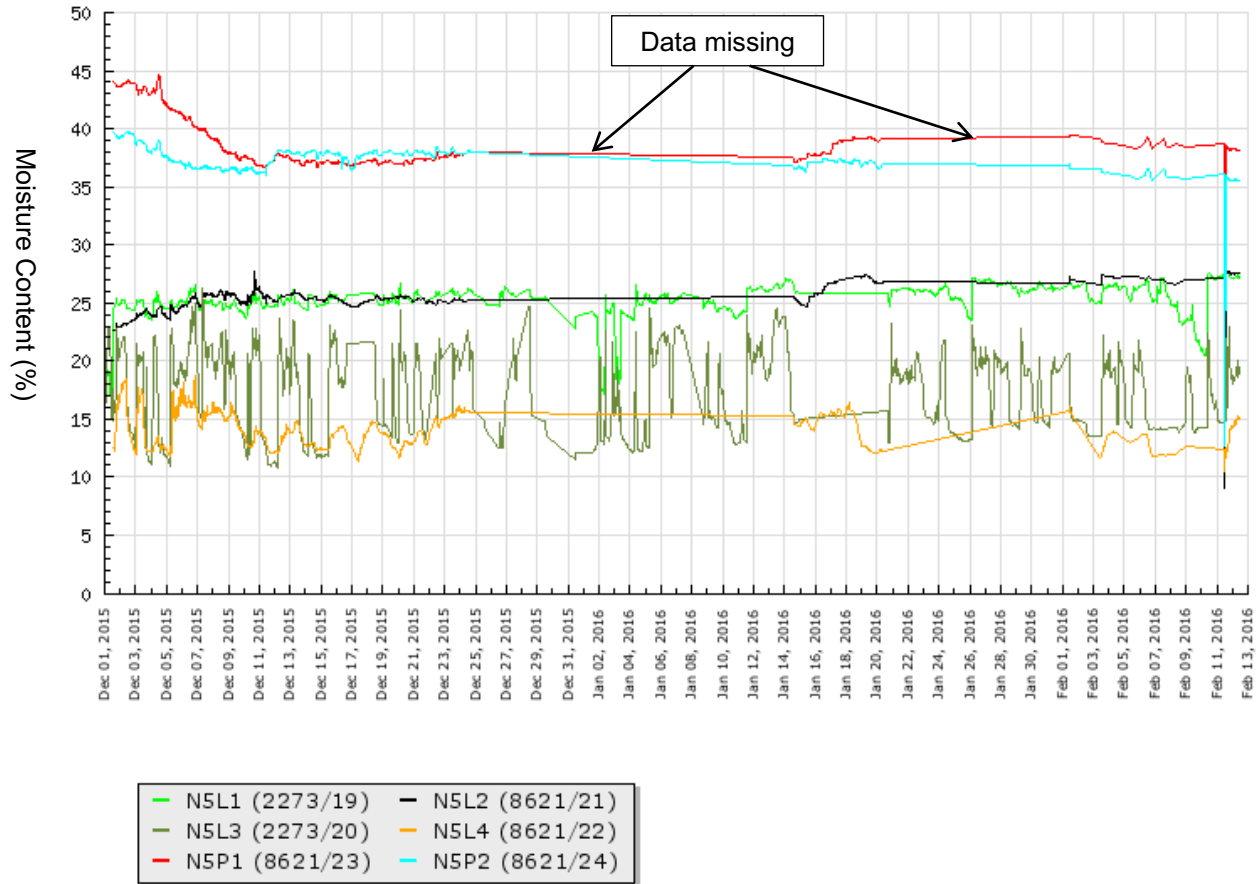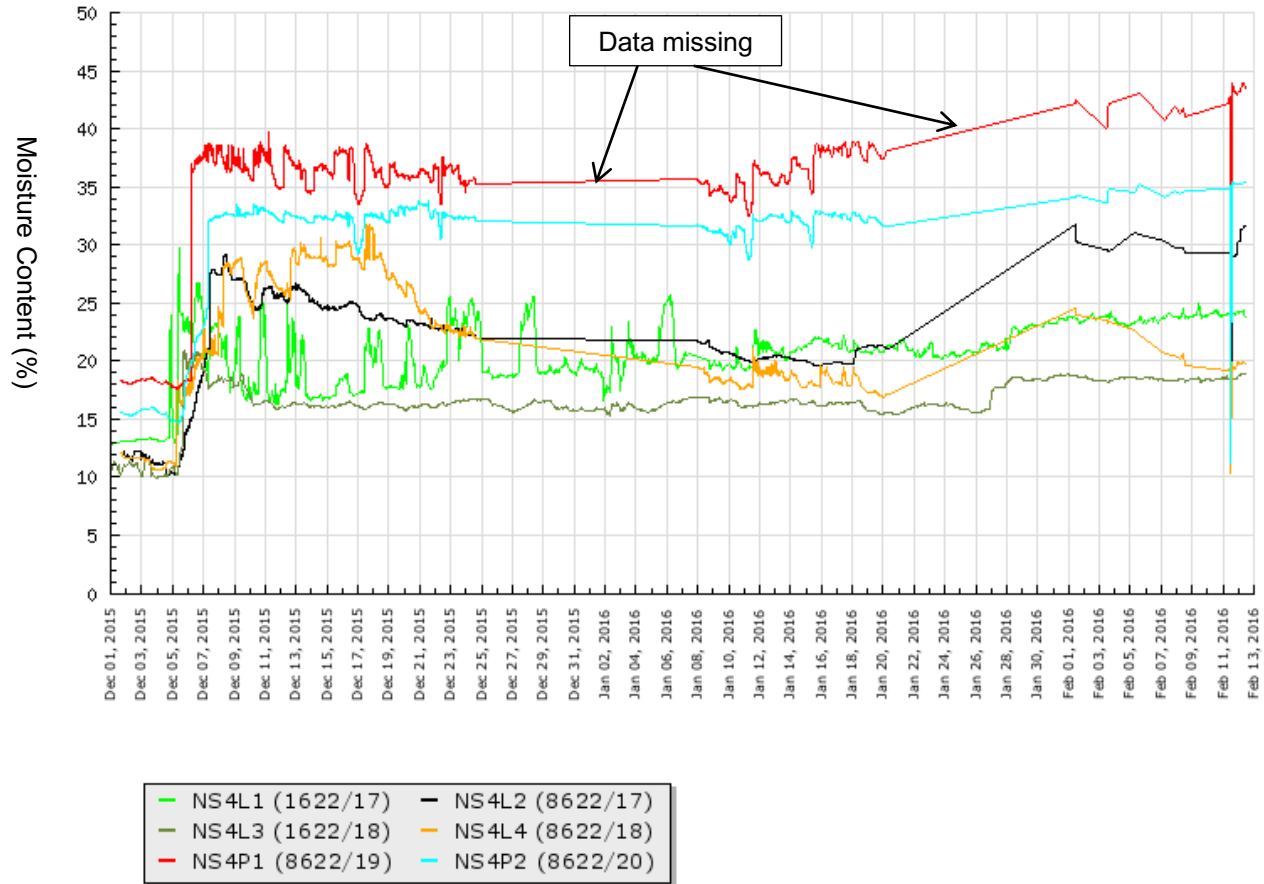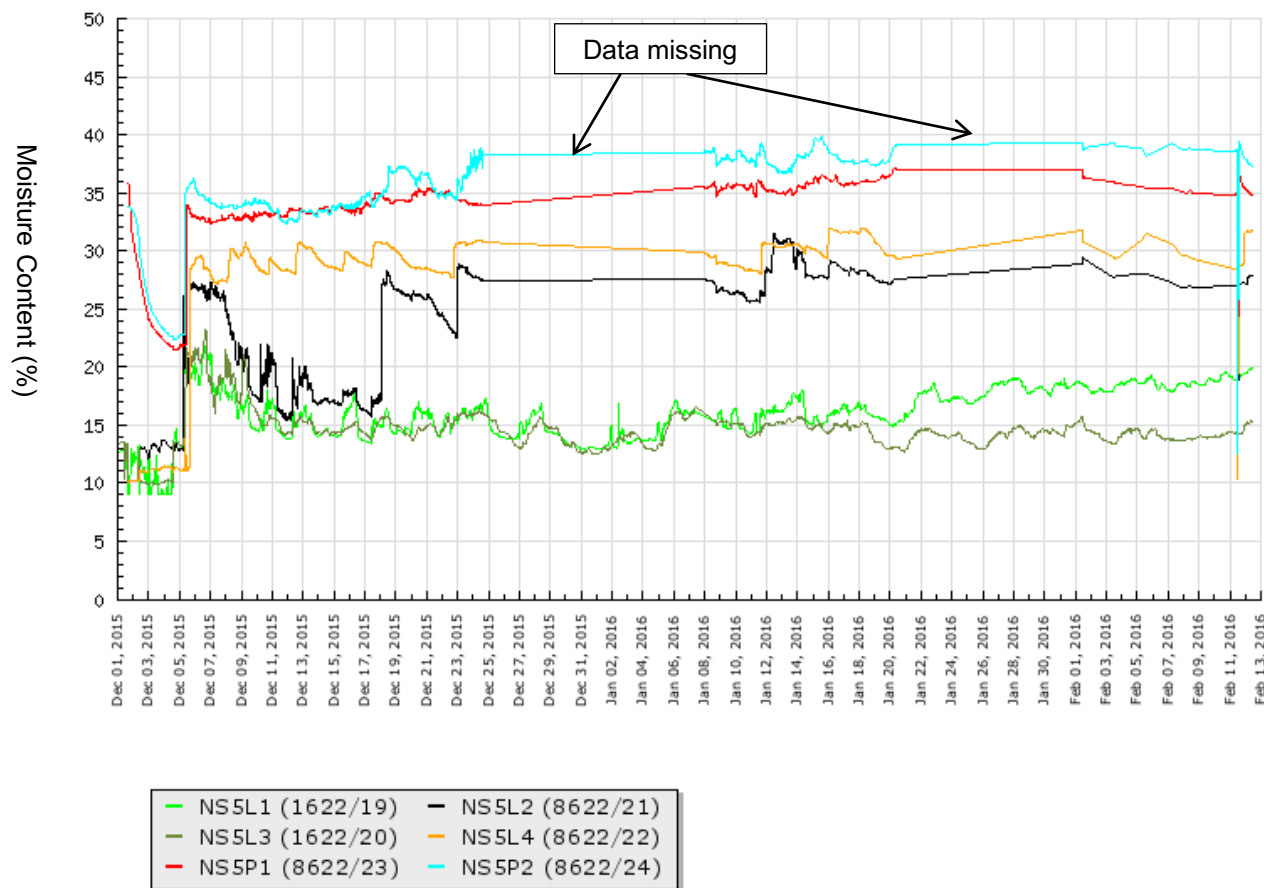P—plywood; P1, P2—top surface of plywood

Figure 17   Moisture content readings from sensors installed in assembly NS5 with a permeable membrane above plywood

Note: L—boards of NLT; number after "L": 1, 2—top surface; 3, 4—central

P—plywood; P1, P2—top surface of plywood

5.2   Wetting and Drying of NLT Assemblies under Laboratory Conditions

5.2.1   *Drying in Shed without Space Heating*

The wetting scheme used in the laboratory through controlled spray of water was more intense than the natural wetting during the outdoor exposure. For an unprotected NLT beam (i.e., S1, Figure 18), the sensors installed in the surface of NLT showed MCs over 40%, indicating that these locations were very wet and may be beyond the upper measurement limit, when the drying test started in the shed. Measurements from those locations suggested the NLT beam dried relatively quickly under the sheltered conditions and the MCs reached 20% after about two months. However, the central measuring locations showed MCs close to 30% at the beginning; moreover, the MC stayed high for an extensive period of time. They slowly dropped to 20% at the end of August, five months into the drying test after a drier than normal summer. This might have led to decay but the specimen was not opened for inspection.

When there was plywood sheathing on the top (i.e., S2, Figure 19), the NLT beam stayed relatively dry except for a measuring location in the bottom surface, which could have been wetted by water dripping or splashing. Nevertheless, this location dried relatively quickly. The plywood showed very high MCs, exceeding the upper limit of 45% of the MC measurement system after the laboratory wetting procedure. But it dried relatively quickly, with the MCs falling below 20% in mid-June, after about two months and a half in the shed. When there was a gap in the sheathing (Figure 20), not only the plywood itself but also the NLT beam below showed considerable wetness, similar to the results from the outdoor exposure test. It appeared that the surface of NLT immediately below the plywood was actually gaining moisture, with the MC increasing for about two months until the end of May. Some moisture could have transmitted from the moisture-saturated plywood to the solid wood below. When a layer of building paper was used for protection, either being installed between sheathing and NLT (i.e., assembly S4) or above the sheathing (i.e., S5) (Figure 21), some moisture was still able to pass the sheathing and reach the NLT below. The NLT appeared to be slightly damp with a surface (below plywood) MC around 20%. Compared to the outdoor exposure test (Section 5.1), this laboratory test appeared to better demonstrate the risk of NLT due to moisture entrapment as well as the moderate level of on-site protection that may be provided by building paper.

Figure 18   Moisture content readings from sensors installed in S1 beam without sheathing on top

Note: L—boards of NLT; number after "L": 1, 2—top surface; 3, 4, 5, 6—central; R—bottom

Figure 19   Moisture content readings from sensors installed in S2 beam and plywood sheathing

Note: L—boards of NLT; number after "L": 1, 2—top surface; 3, 4—central; R—bottom
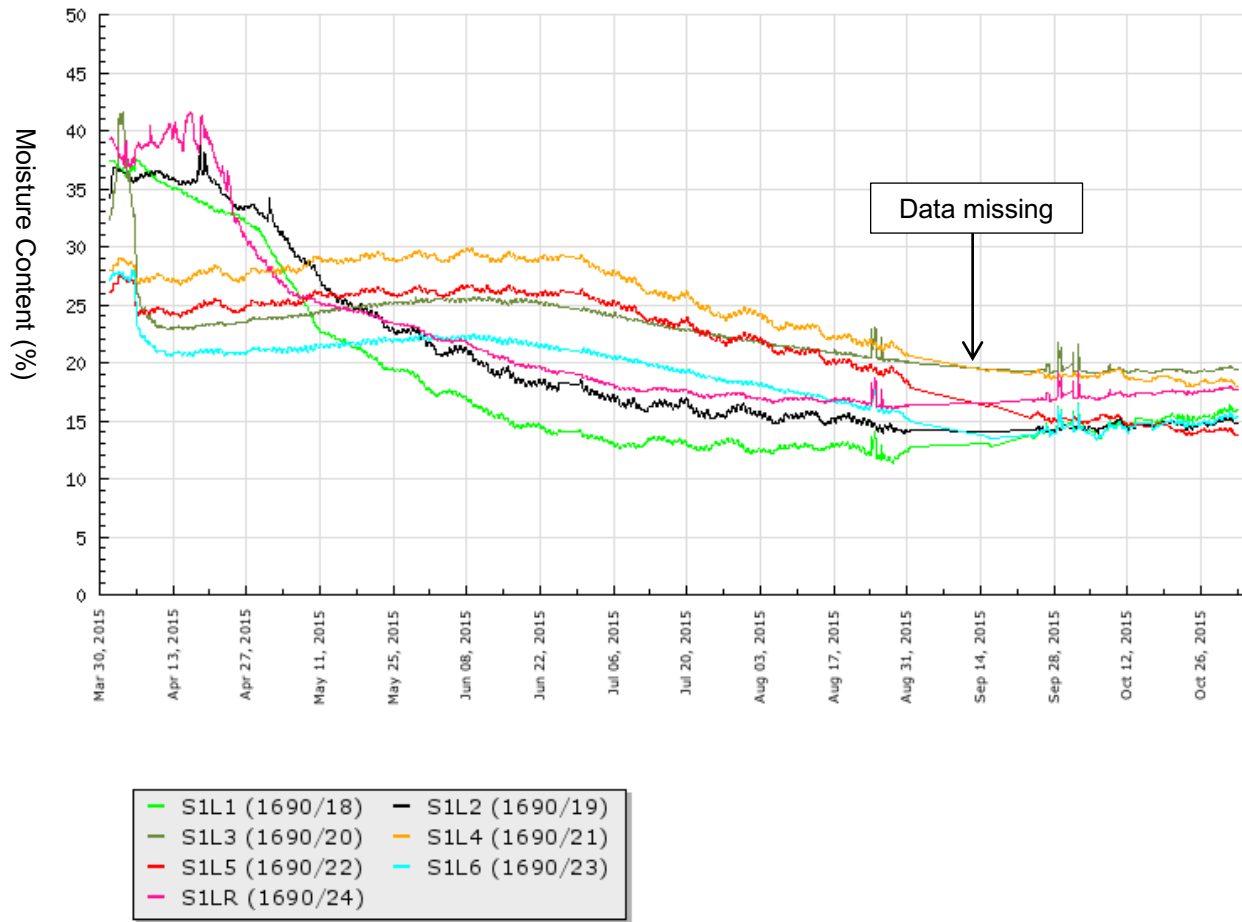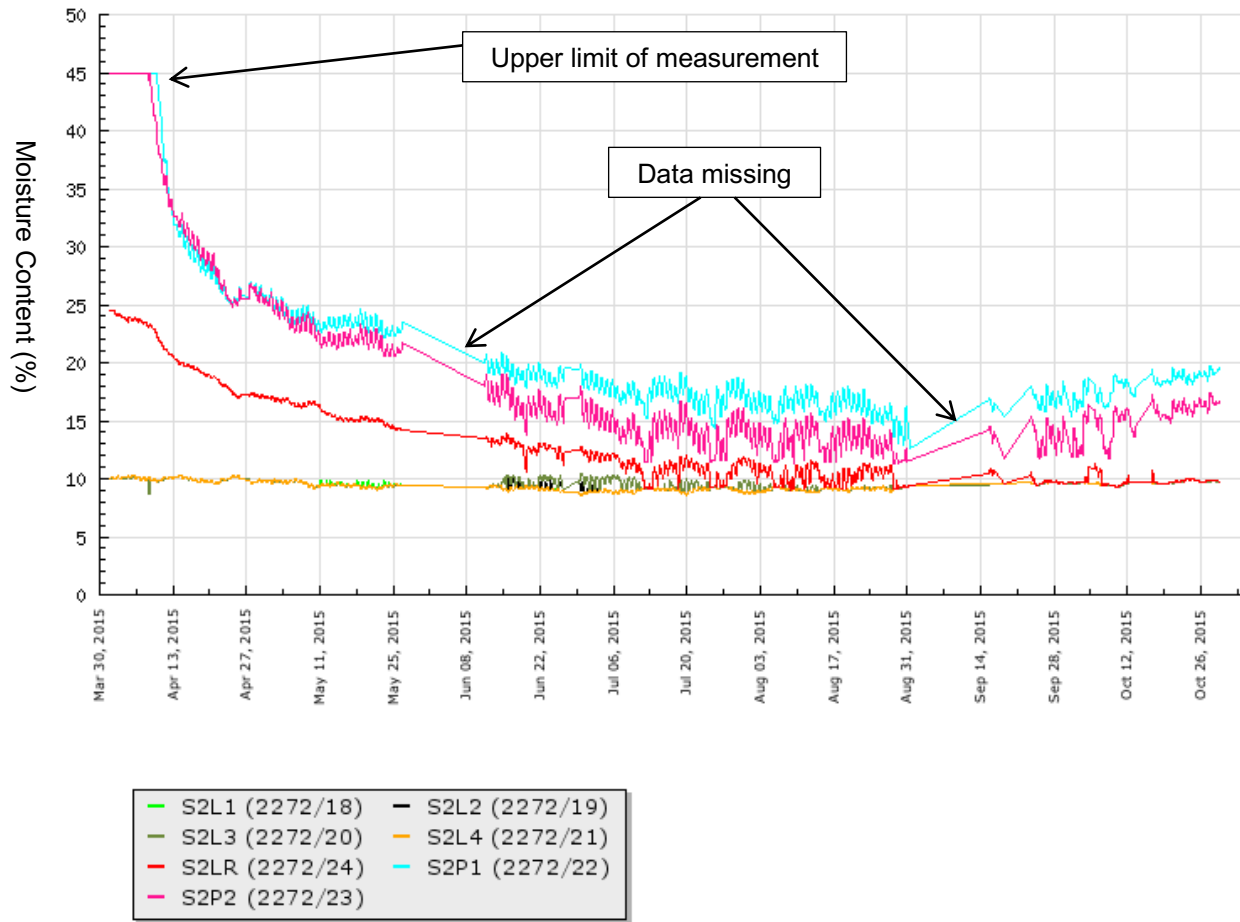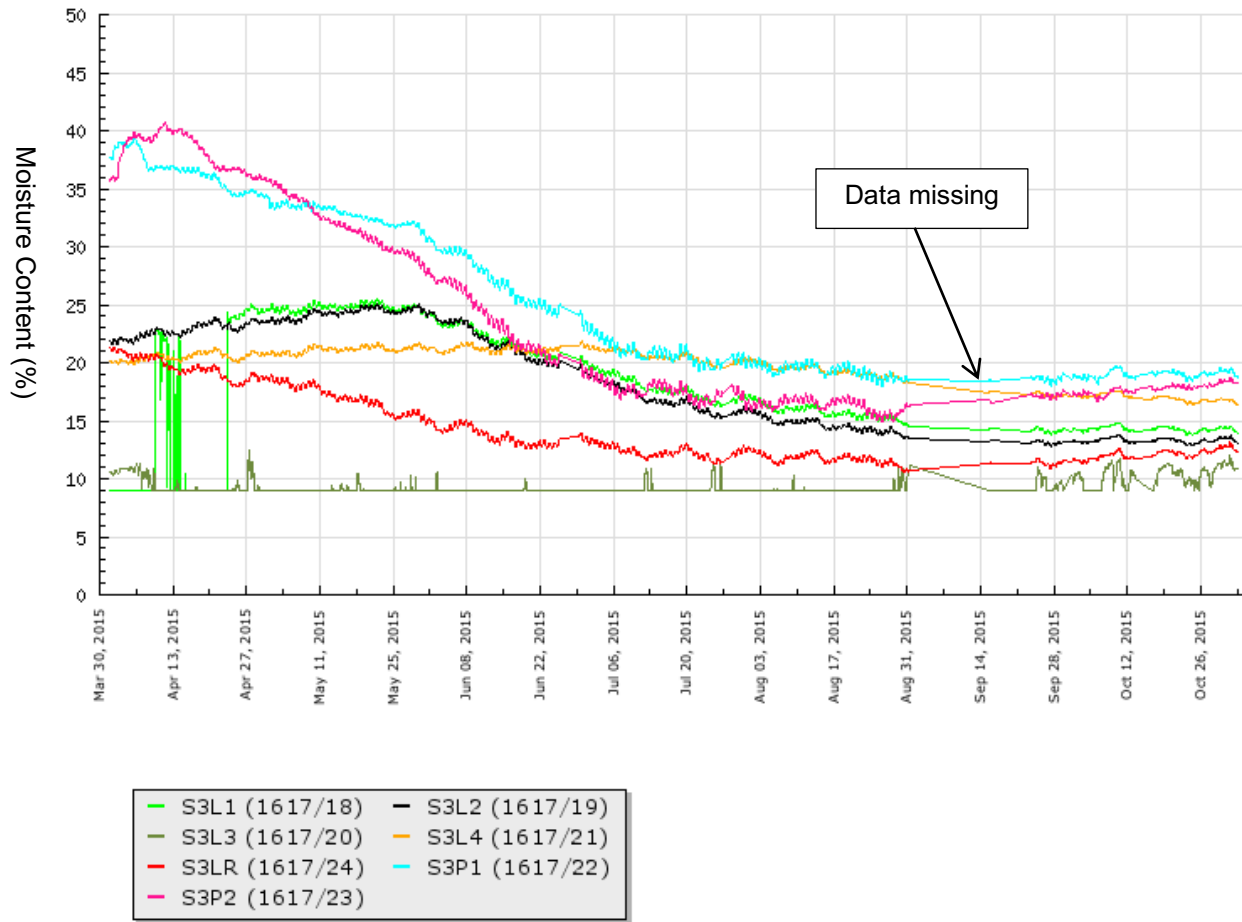P—plywood; P1, P2—middle layer of plywood

Figure 20   Moisture content readings from sensors installed in S3 beam and plywood sheathing

Note: L—boards of NLT; number after "L": 1, 2—top surface; 3, 4—central; R—bottom
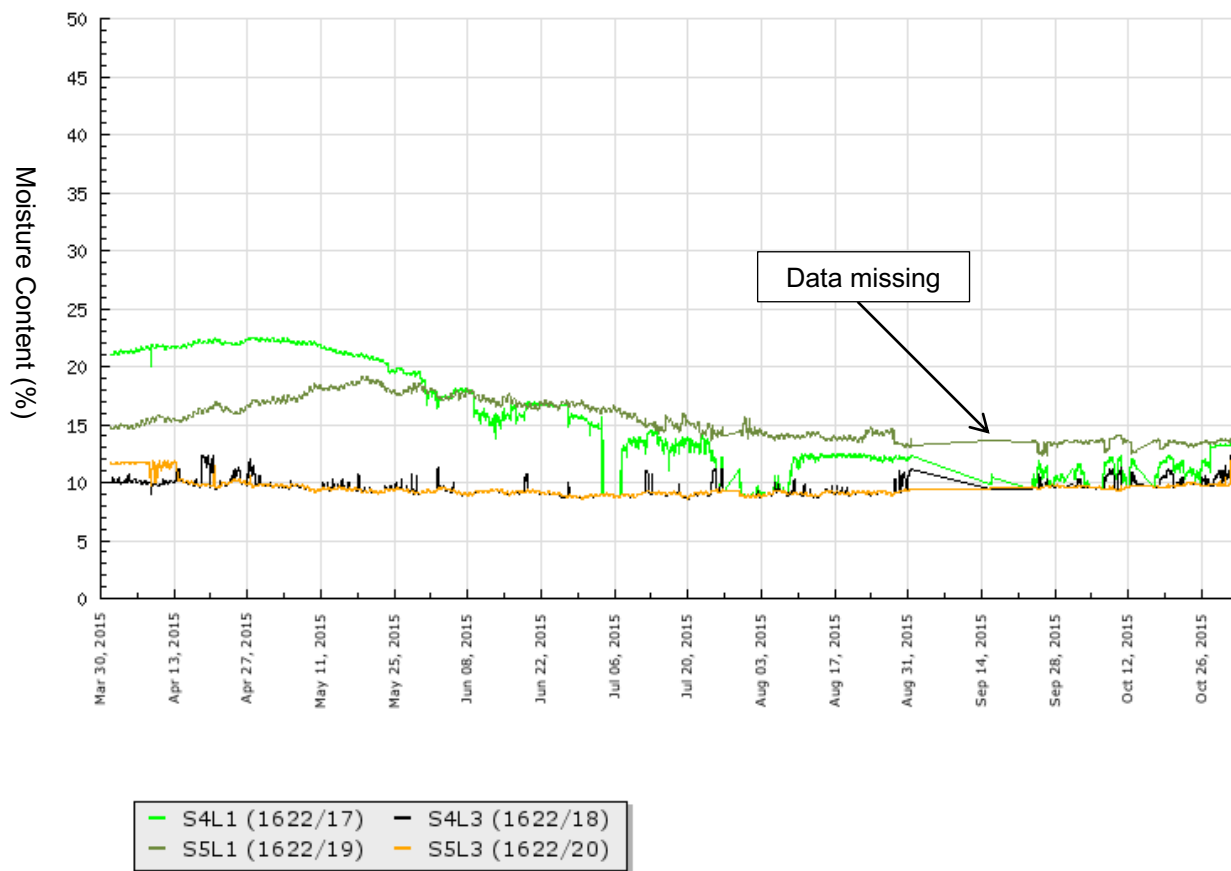P—plywood; P1, P2—middle layer of plywood

Figure 21   Moisture content readings from sensors installed in S4 and S5 beams

Note: L—boards of NLT; number after "L": 1—top surface; 3—central

5.2.2   *Drying above a Plywood Box with or without Heating*

Forced drying methods, typically space heating can be provided to accelerate drying during construction in a relatively convenient and cost-effective way, if needed. This test aimed to assess the effect of space heating on drying NLT assemblies. It should be pointed out that the laboratory wetting conducted for the NLT test assemblies of Group 3 was the most severe since each NLT beam and plywood sheathing was individually sprayed with water before being assembled. It appeared that space heating, provided in the plywood box below, dried the reference plywood specimen (i.e., B1) relatively quickly, although the plywood was covered with a vapour-impermeable membrane on the top (Figure 22). The surface measuring locations in the top layer of plywood right below the membrane, i.e., a location with the highest risk reached a MC of about 20% after one month and a half in the heating season (April, May). Apparently moisture was able to dissipate from underneath, in the direction opposite to the temperature gradients. Increasing temperature in the wet wood increased the internal vapour pressure and the increased vapour pressure gradients must have driven the moisture towards the heated box below. This drying ability under reversed temperature differentials may not be anticipated by all practitioners, for example, who believe that wet walls cannot dry to the interior of a

building in the absence of an interior vapour barrier. The test demonstrated the effectiveness of space heating in drying light wood-frame construction before enclosure in a wet climate.

When a wetted test assembly which included both NLT beam and plywood with no membrane on the top was supported above a plywood box without heating (i.e., assembly B2, Figure 23–Figure 24), both plywood and NLT beam dried slowly. The plywood reached a MC of 25% at the end of August and actually stayed at MCs above 20% throughout the entire test period of seven months. Even the top surface, which was exposed to the ambient environment in the shed, dried slowly due to the large amount of moisture it absorbed during the wetting procedure and the small drying forces available. Drying of the plywood could also have been retarded by the wet NLT beam below. Most measuring locations in the NLT beam stayed above a MC of 20%, except the bottom surface, with the MC reduced below 20% in about two months. When the same assembly was supported on a plywood box with heating provided inside (i.e., B3) (Figure 25–Figure 26), the drying of both plywood and NLT beam appeared to slightly speed up, particularly the plywood over the summer (Figure 25). The MCs in plywood reduced to around 20% after about two months. But the central areas of NLT did not drop to 20% until the end of August, after about five months into the drying test.

The worst scenario occurred when the assembly was covered with a vapour-impermeable membrane, i.e., assembly B4 and there was no heating in the plywood box underneath (Figure 27–Figure 28). The MC readings from most measuring locations in both of the plywood and the NLT beam overall stayed flat after the laboratory wetting. The only exception was the bottom surface of the NLT beam, which started drying in late June, when it was warm and dry. Providing heat in the box (i.e., assembly B5) appeared to slightly speed up drying of the portion of the NLT beam right above the heated space (Figure 30); but the heating did not improve drying of the plywood sheathing on the top (Figure 29). The MC readings from the top and middle layer of the plywood actually increased in the summer. This must have been caused by moisture movement resulting from increased internal drying forces (e.g., increased vapour pressure due to the warmer conditions); however, moisture dissipation to the exterior was completely stopped by the impermeable membrane on the top. See Table 3 for a comparison of these five test assemblies and their implications for on-site moisture protection.

The test indicates that when materials are wet, they should be dried before assembly or enclosure. An assembled system will have greatly reduced drying ability, even when there is no impermeable material (e.g., vapour-impermeable membrane, plastic foam) to stop moisture evaporation, and forced drying is provided. The water and vapour permeability of a material has a large effect on the drying ability. Most wood products are not permeable enough to allow moisture dissipation quickly; the resistance to moisture movement internally also greatly increases with increase in thickness (Kumaran 2002; Karacabeyli and Douglas 2013). Space heating is most effective in accelerating drying of thin or small elements (e.g., plywood) as shown above. But its effectiveness will greatly reduce with increase in the depth of products/assemblies, since wood is a good insulator to reduce heat conduction. Some level of air flow can improve heat transfer and consequently the drying rates; but the boards of NLT are usually in close contact to meet structural requirements. The gaps between the boards are further minimized in wet assemblies resulting from swelling, particularly when the assembly has been installed and structurally confined around its perimeter. However, when NLT becomes wet during construction, heating plus ventilation, such as in a means of blowing hot air, remains probably the most practical

solution to accelerating drying and is strongly recommended, especially in a cold and damp climate. Ideally the hot air should be in direct contact with the NLT surface, i.e., removing any sheathing or membrane on the top, if it is present. Any impermeable membrane should always be removed prior to use of forced drying since they completely stop moisture dissipation from the particular surface.

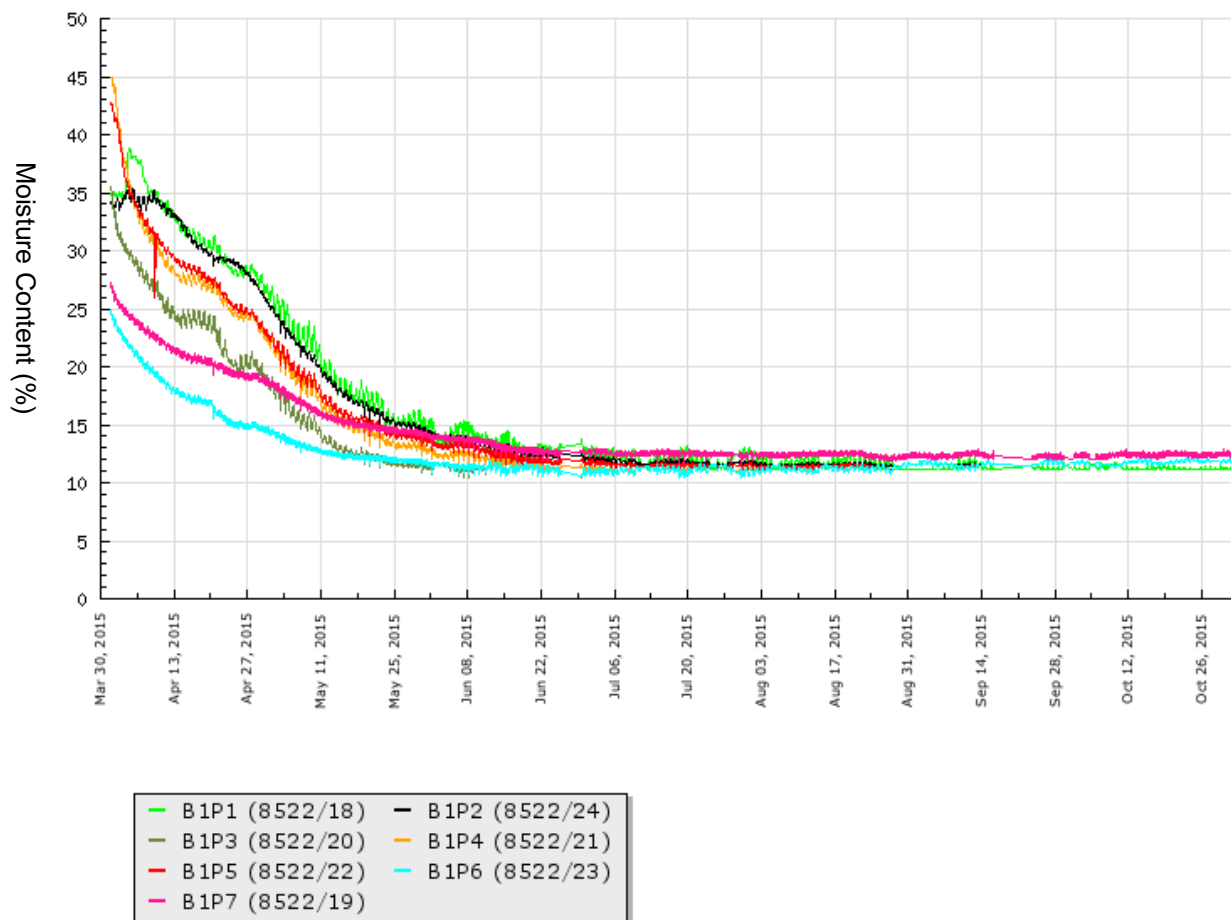**Figure 22   Moisture content readings from sensors installed in plywood sheathing of assembly B1**

Note: P—plywood; number after "P": 1, 2—top layer; 3, 4, 5—middle layer; 6, 7—bottom layer of plywood

Figure 23   Moisture content readings from sensors installed in plywood sheathing of assembly B2 (no heating or membrane)

Note: P—plywood; number after "P": 1, 2—top layer; 3, 4, 5—middle layer; 6, 7—bottom layer of plywood

Figure 24　Moisture content readings from sensors installed in beam of assembly B2 (no heating or membrane)

Note: L—boards of NLT; number after "L": 1—top surface; 3, 4, 5, 6—central; R—bottom
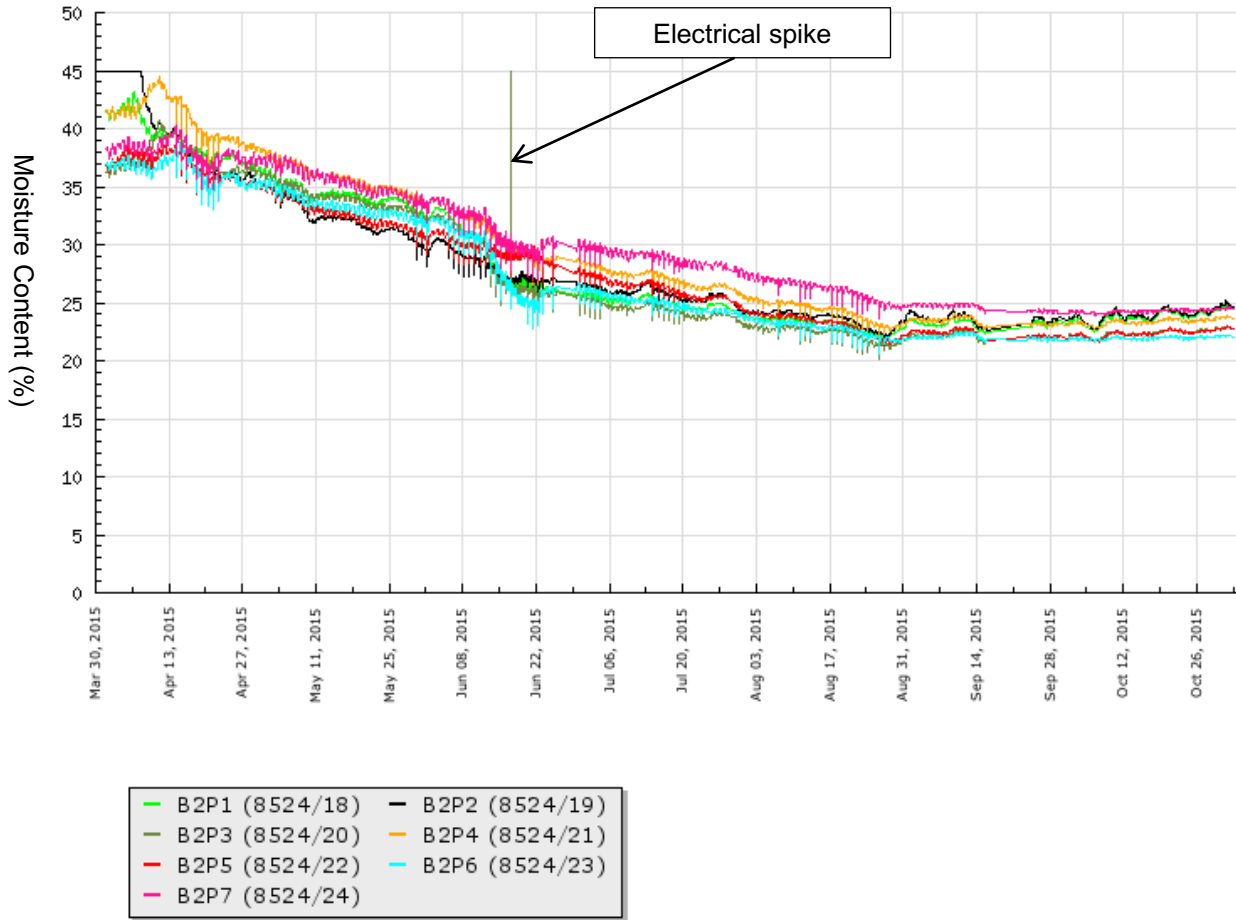
Figure 25   Moisture content readings from sensors installed in plywood sheathing of assembly B3 (no membrane, with heating)

Note: P—plywood; number after "P": 1, 2—top layer; 3, 4, 5—middle layer; 6, 7—bottom layer of plywood

Figure 26   Moisture content readings from sensors installed in beam of assembly B3 (no membrane, with heating)

Note: L—boards of NLT; number after "L": 1, 2—top surface; 3, 4, 5, 6—central; R—bottom

Electrical spike

Legend:
- B4P1 (8526/18)
- B4P2 (8526/19)
- B4P3 (8526/20)
- B4P4 (8526/21)
- B4P5 (8526/22)
- B4P6 (8526/23)
- B4P7 (8526/24)
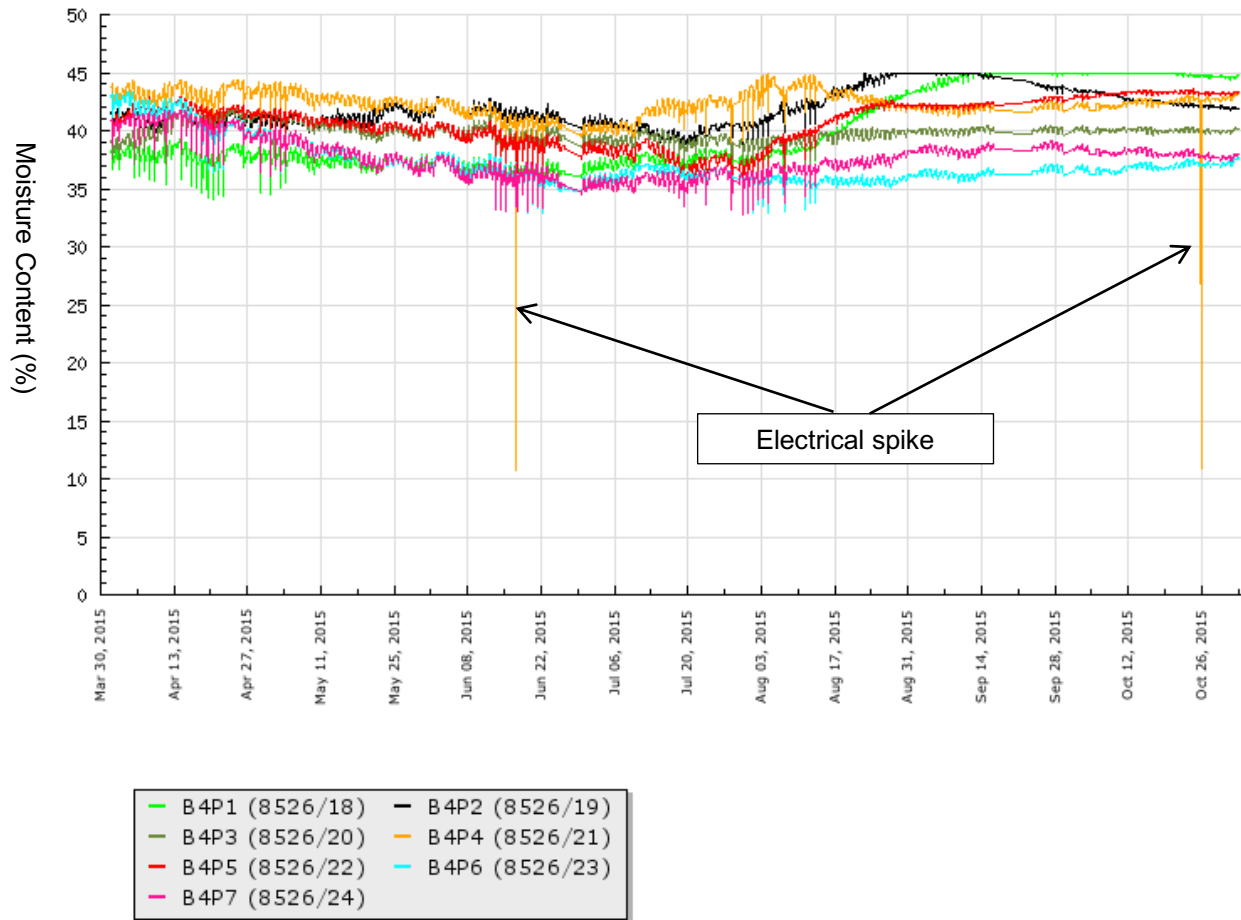
Figure 27 Moisture content readings from sensors installed in plywood sheathing of assembly B4 (no heating, with membrane)

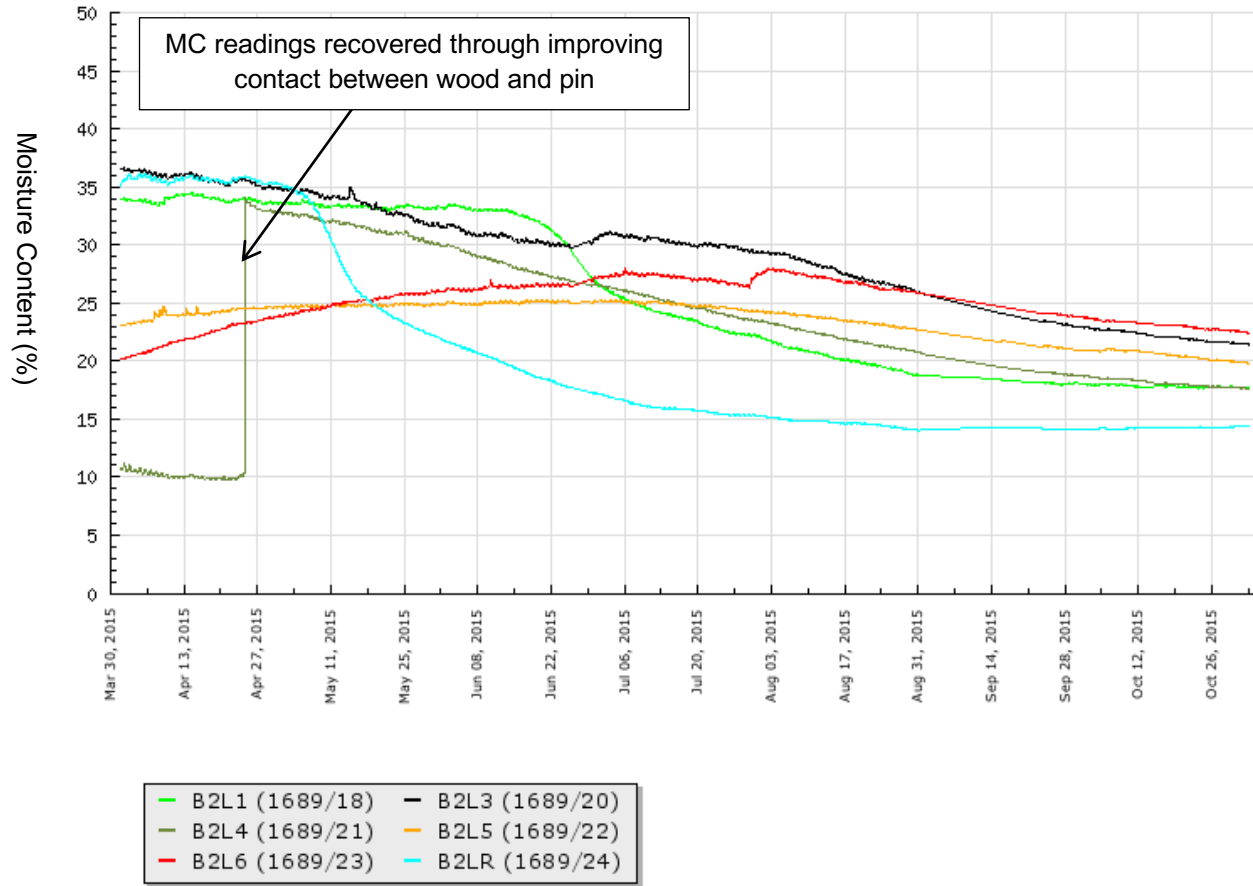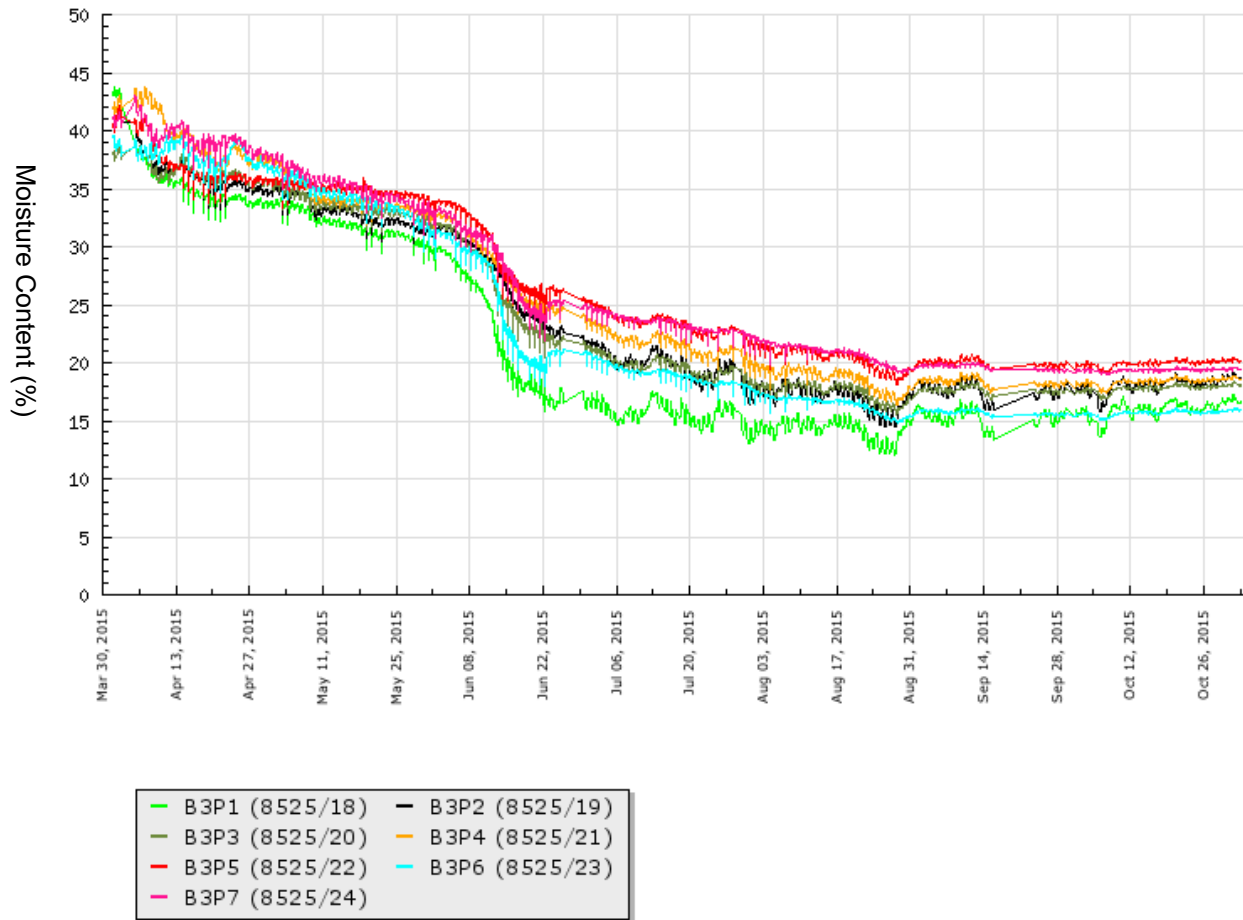Note: P—plywood; number after "P": 1, 2—top layer; 3, 4, 5—middle layer; 6, 7—bottom layer of plywood
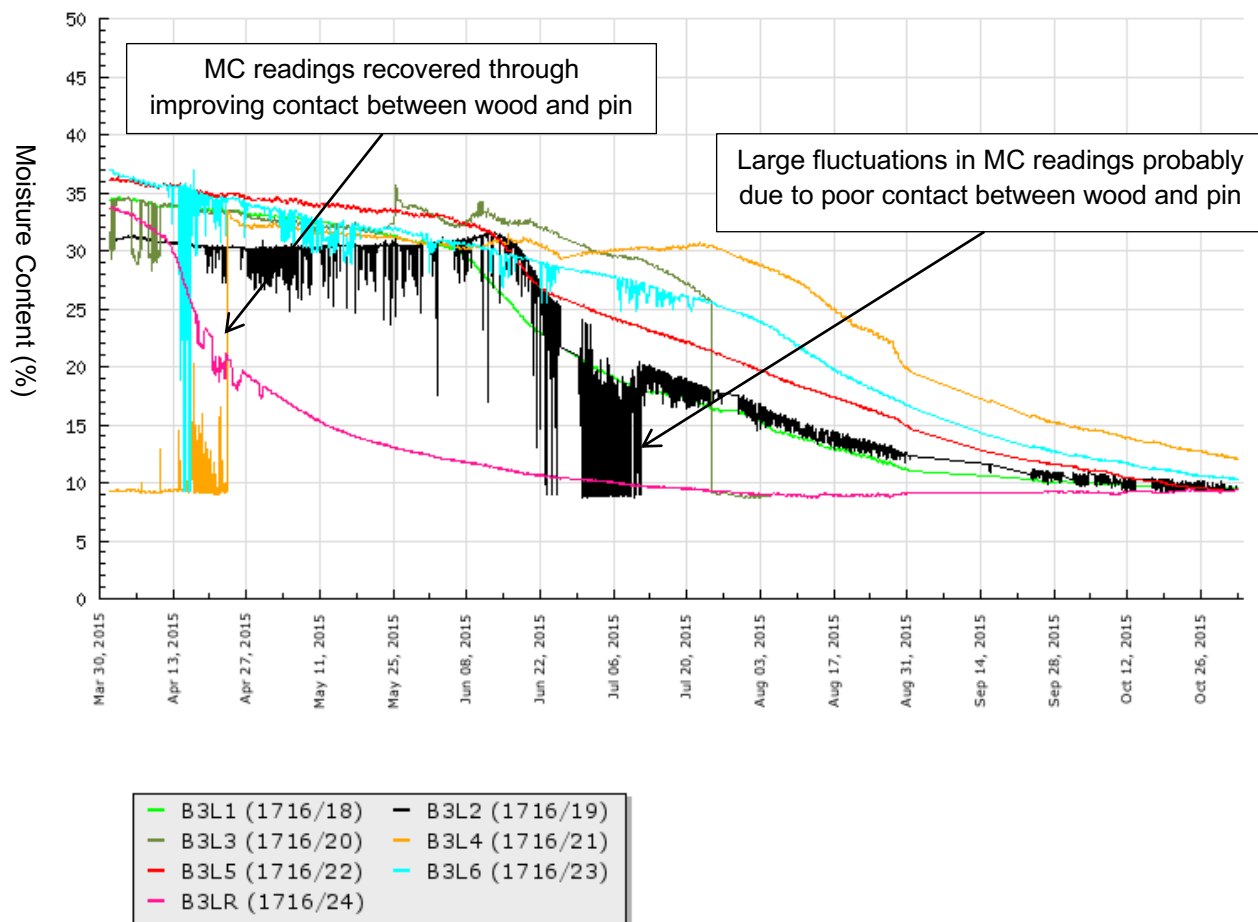
Figure 28 Moisture content readings from sensors installed in beam of assembly B4 (no heating, with membrane)

Note: L—boards of NLT; number after "L": 1, 2—top surface; 3, 4, 5, 6—central; R—bottom

Figure 29   Moisture content readings from sensors installed in plywood sheathing of assembly B5 (with both heating and membrane)

Note: P—plywood; number after "P": 1, 2—top layer; 3, 4, 5—middle layer; 6, 7—bottom layer of plywood

Figure 30   Moisture content readings from sensors installed in beam of assembly B5 (with both heating and membrane)

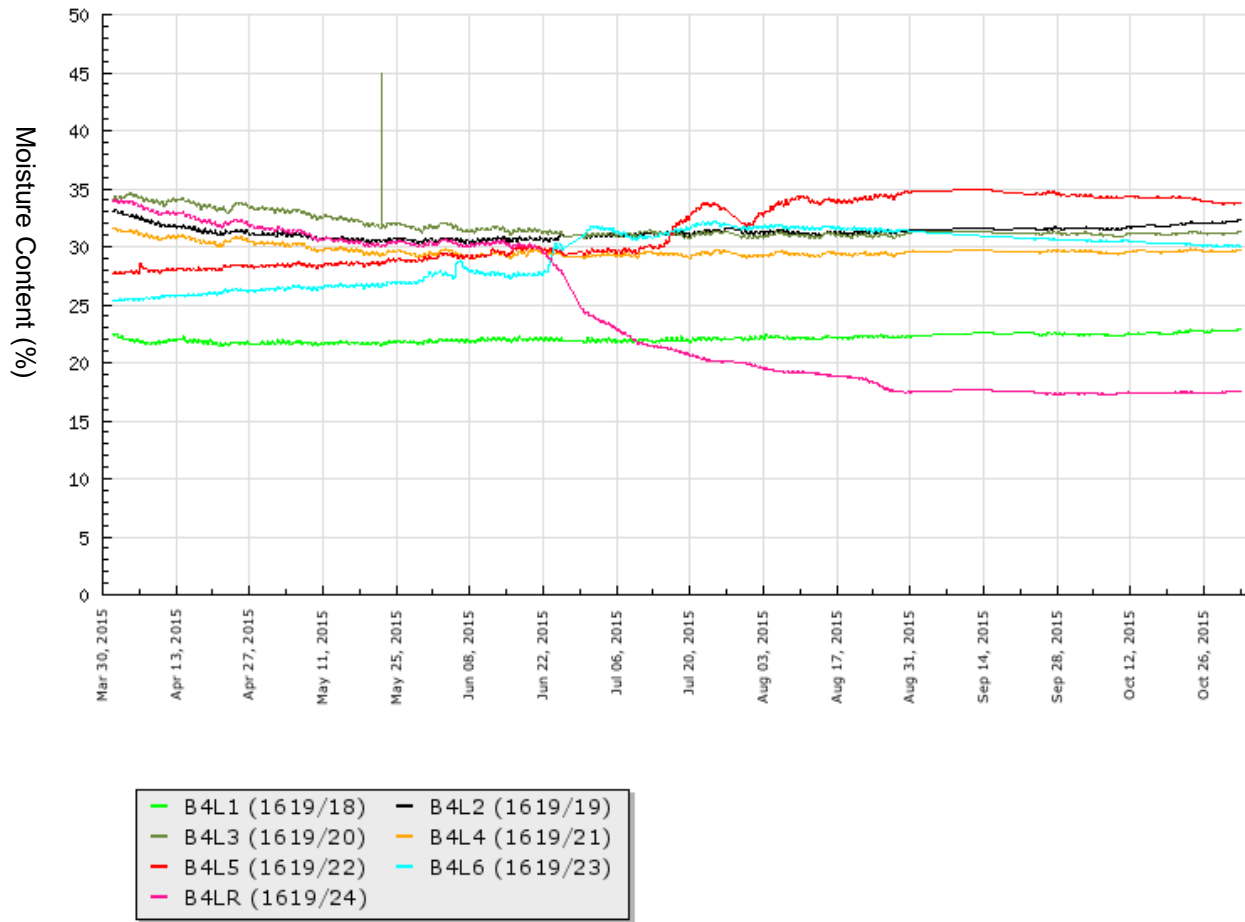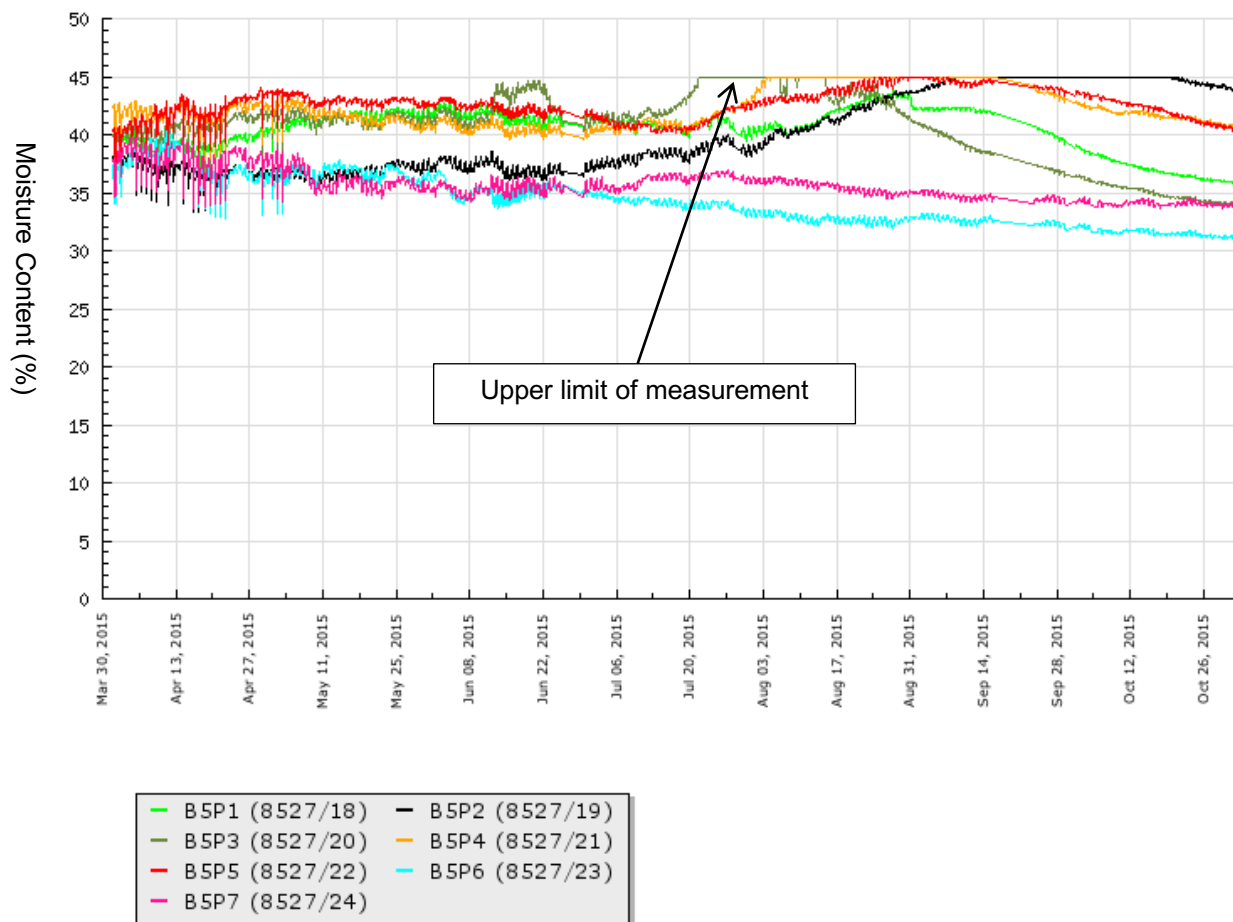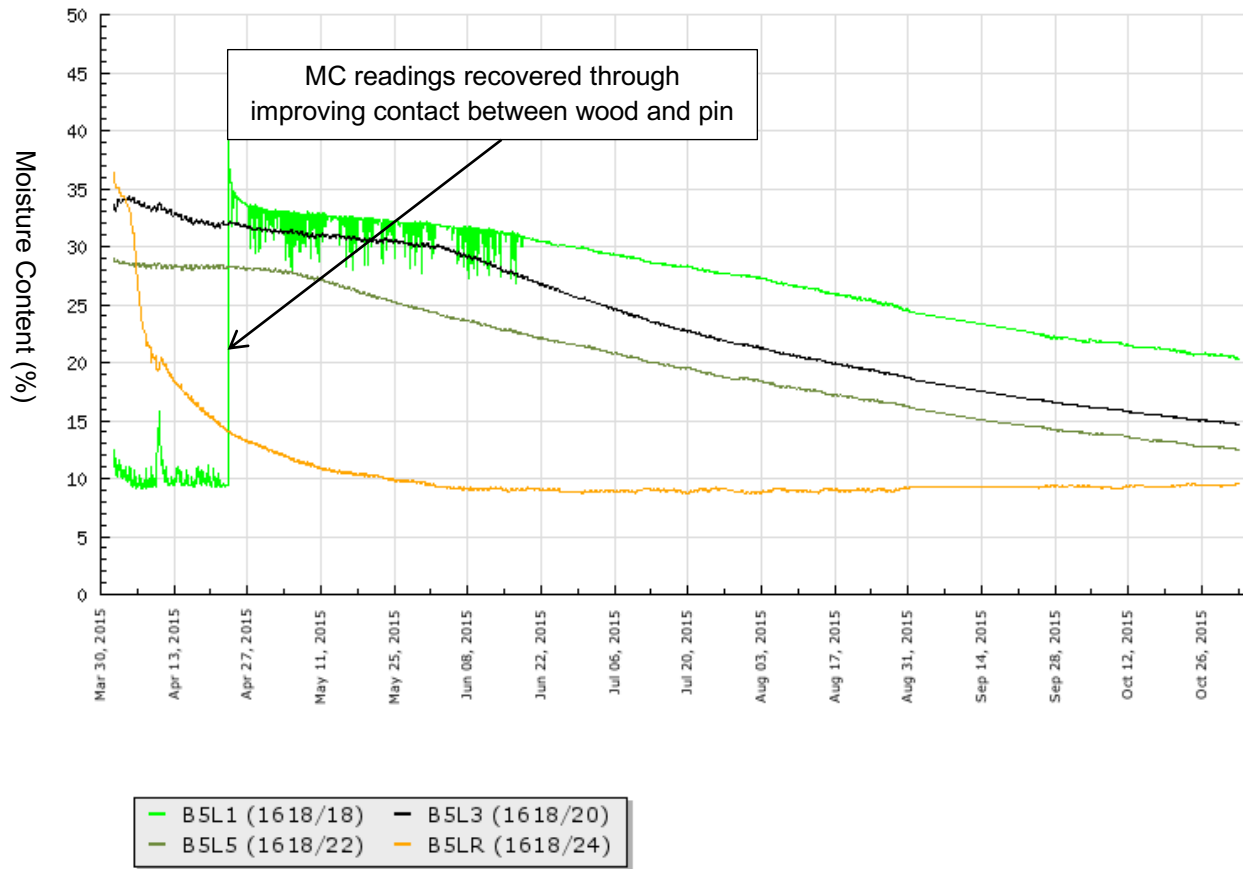Note: L—boards of NLT; number after "L": 1—top surface; 3, 5—central; R—bottom

Table 3   Comparison of drying performance based on testing of Group 3

Test Assembly	Space heating provided?	Drying performance	Implications for practical use
B1: Plywood sheathing covered with an impermeable membrane on the top	Yes	The plywood dried relatively quickly. The surface layer, being immediately below the impermeable membrane and the most risky area, reached a MC of 20% after one month and a half in a heating season (April, May).	Space heating is effective in drying thin panels even under reversed temperature differential conditions. In general space heating is effective in drying wetted light wood-framing before enclosure.
B2: NLT + plywood, no membrane above the plywood	No	Both plywood and NLT dried slowly without any forced drying mechanism, even when there was no membrane to prevent moisture dissipation. Most measuring locations stayed at MCs above 20% throughout the entire drying test of seven months.	Natural drying cannot be replied on for drying NLT once severe wetting occurs, even when there is no membrane covering the surface. More proactive measures are required to dry NLT assemblies.
B3: NLT + NLT, no membrane	Yes	Heating slightly sped up drying of both plywood and NLT. The MCs in plywood dropped to around 20% after about two months. The wetted central areas of NLT did not reach 20% until the end of August, after about five months into the drying test.	Space heating is helpful but may not be highly effective to dry NLT, once severe wetting occurs. More proactive measures, such as by blowing hot air, are desired to dry NLT.
B4: NLT + plywood, with a vapour-impermeable membrane on the top	No	This was the worst-case scenario. Neither NLT nor plywood dried.	Wet materials, in large dimensions in particular, should not be assembled and should always be dried before assembly. Wet wood should never be covered with an impermeable membrane or other impermeable materials (e.g., low-permeance insulation).
B5: NLT + plywood, with an impermeable membrane on the top	Yes	Heating sped up drying of NLT but the MCs at risky locations stayed above 20% for the entire seven months of testing. Heating did not dissipate any moisture from the plywood sheathing on the top, which was too distant from the source of heating.	Wet wood should never be covered with an impermeable membrane or other impermeable materials. Heating is generally helpful in drying wood but its effectiveness needs to be assessed when drying a large built-up assembly, such as NLT. Other measures may need to be taken together in order to accelerate drying.

5.3   Preliminary Assessment Results for CLT

The two CLT reference specimens in this study provided further indications of wetting and drying behaviour of CLT products by showing changes in MC at different locations through the moisture pin sensors installed. A previous laboratory test (Wang 2014) assessed aggregated wetting and drying rates of CLT and other specimens based on their weight changes. During the outdoor test, the MCs measured in the CLT specimen were gradually elevated at the beginning of the test, i.e., from March to May, when it rained frequently (Figure 31). The readings from most measuring locations, except in the bottom layer and the centre of the central board, increased from "non-detectable" values (i.e., below the lower measurement limit of 9%) to over 25%. They then stayed at the high values over the dry summer (June-August); but did not significantly increase either, in the following rainy season (September-October). It was interesting to notice that the readings from the sensors C1L3 and C1L5, located close to the two edges of the central board of the middle layer, were among the highest. The small gaps between board edges and the blue-stained sapwood in this case could have both contributed to trapping moisture (Figure 32).

By comparison, the laboratory assessment presented a slightly different picture for the wetting and drying behaviour of CLT (Figure 33). It was found that the MC at any measuring location was below 20% after the intense wetting procedure in the laboratory. During the drying test under the sheltered conditions in the shed, the MC readings did not reduce considerably. These two CLT specimens indicated that the time of exposure, i.e., wetting time, was a key condition for the core of a CLT panel to gain MC; however, the drying was very slow once moisture penetrated deep in the panel. The MC at the surface of each board in a CLT panel would be anticipated to be higher than that measured in the centre. This was not measured, but we noticed that decay was identified in the end grain of boards in the reference CLT specimen, which was left to dry in the shed following the laboratory wetting procedure (Figure 34). Note such decay initiation is not specific to the material itself but had mostly resulted from the conditions of the test. The impermeable membrane used for edge sealing must have stopped moisture evaporation from the wet end grain and have created favourable conditions for decay to initiate and progress over a period of 8 months under the relatively warm conditions. This confirms the importance of maintaining a good drying ability for wood assemblies to ensure long-term durability. Installing an impermeable membrane or other low-permeance materials on wood, mass timber members in particular, needs to be carefully considered (or reconsidered) due to the negative impact it has on the drying ability. This has been emphasized in many best practice guides, such as the CLT Handbooks (Gagnon and Pirvu 2011; Karacabeyli and Douglas 2013).
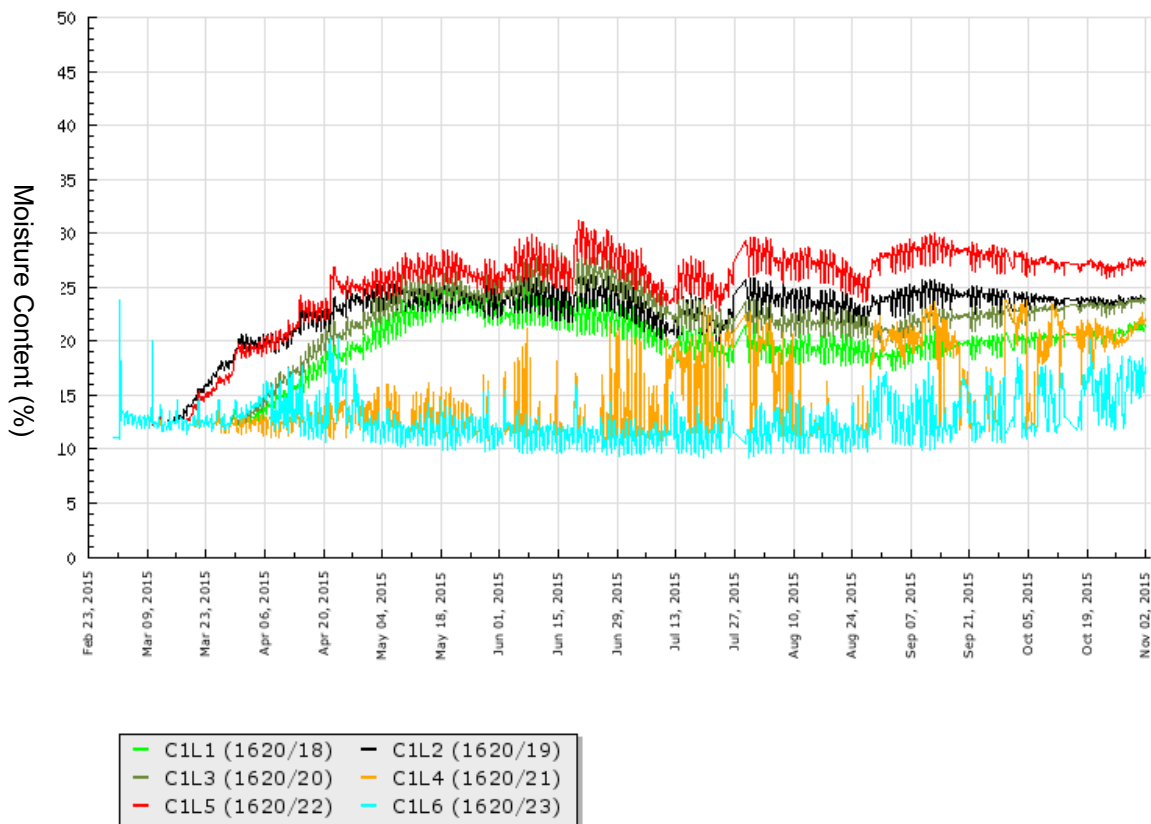
Figure 31 Moisture content readings from sensors installed in cross-laminated timber during outdoor exposure

Note: Number after "L": 1, 2—central top surface board; 3, 4, 5—central board of the middle layer, with C1L3 and C1L5 close to the two edges of the board; 6—centre of the bottom surface board

Figure 32 Picture showing central board of the middle layer, with dark colour of blue-stained sapwood indicating elevated moisture content

Figure 33   Moisture content readings from sensors installed in cross-laminated timber drying in shed following laboratory wetting

Note: Number after "L": 1, 2—central top surface board; 3, 4, 5—central board of the middle layer, with C2L3 and C2L5 close to the two edges of the board; 6, 7—central bottom surface board
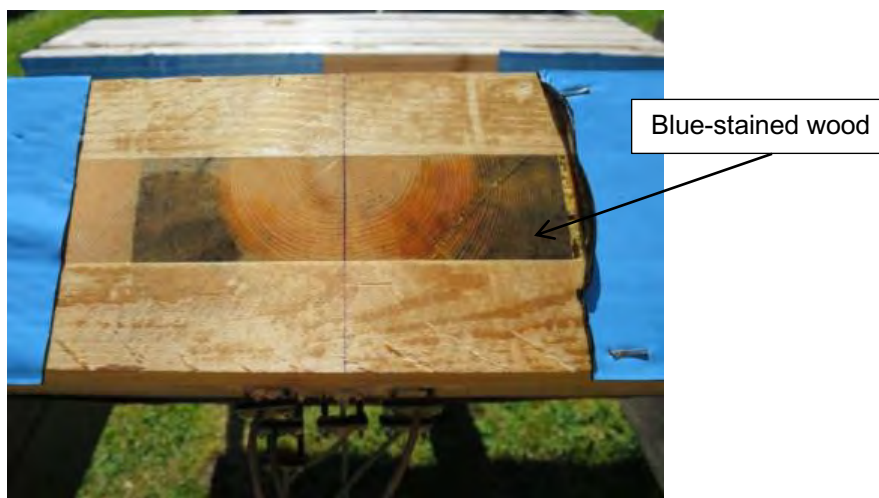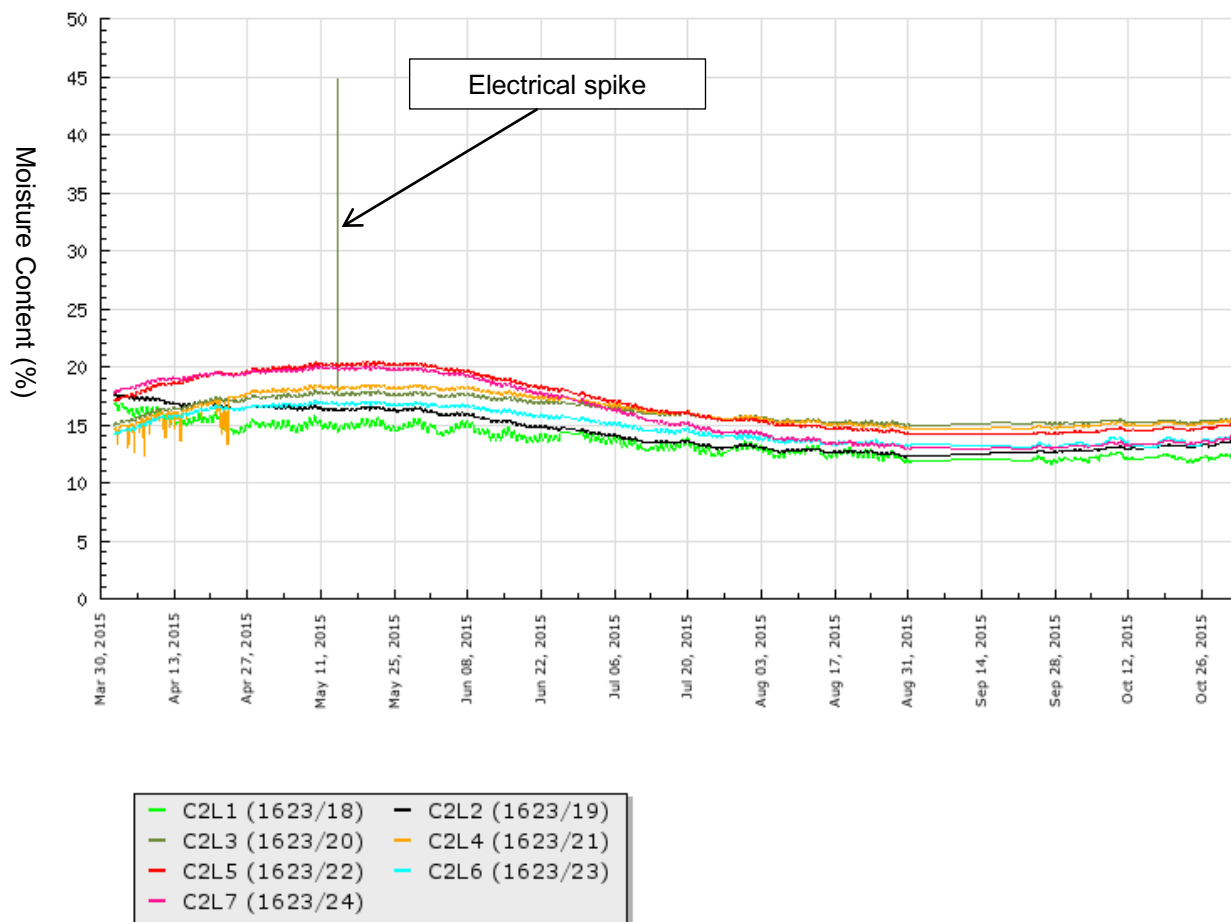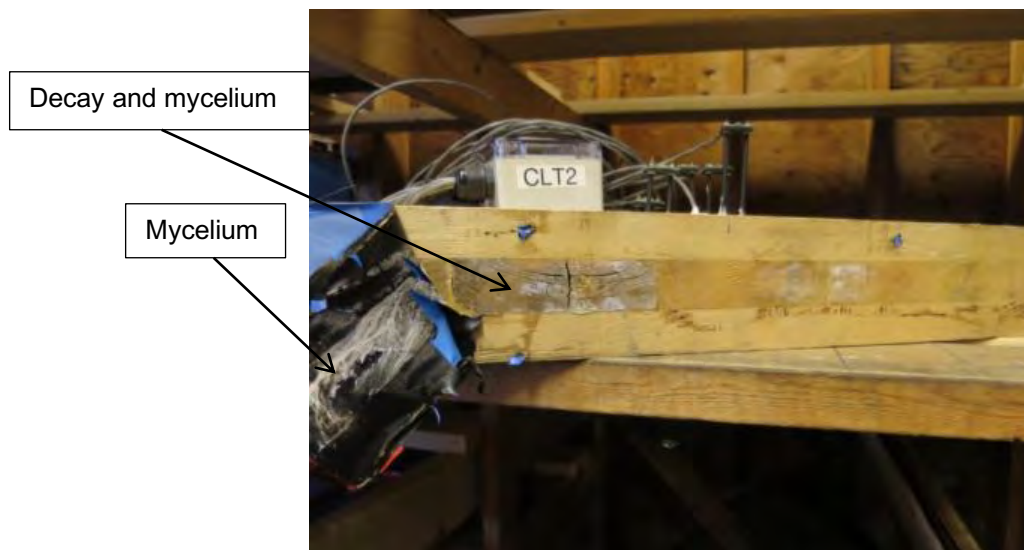
Figure 34   Decay started from end grain with mycelium visible on impermeable membrane after eight months in shed following a laboratory severe wetting procedure

6   CONCLUSIONS

Overall this study confirms that products and assemblies that are susceptible to wetting and have poor drying performance, including NLT, should be protected against wetting during construction under wet weather conditions to prevent durability-related issues. The drying may be very low and take months even when space heating is provided, once severe wetting occurs. On a job site the MC should be checked before enclosure. Resistance-based moisture meters with long pins (probes) may be used to measure the MC in the central area (i.e., the core of NLT member), which will dry the slowest once wetting occurs.

More specific conclusions and implications from this study include:

1. Water penetrated into NLT quickly when it was directly exposed to wetting without any sheathing or membrane on the top. Severe wetting caused the MC in the central area approach or exceed 30% and could take months to dry out.

2. When NLT was covered with plywood prior to wetting, it was protected by the sheathing from water penetration to a small degree; but the areas below gaps (joints) in the sheathing remained risky areas for trapping water. The gaps in pre-installed sheathing should therefore be immediately sealed upon installation to prevent localized moisture entrapment in NLT. Use of tongue-and-groove panels may reduce the level of water penetration through the joints. However, plywood is water-absorptive itself and severely wetted panels will dry slowly under environmental conditions that are not favourable for drying (e.g., the winter season in coastal British Columbia). Therefore, the sheathing of NLT should also be pre-protected, if possible.

3. Wet NLT covered with wet plywood dried very slowly even under space heating conditions. Wet NLT should always be dried prior to further assembly or enclosure.

4. Regarding the concept of installing a vapour-permeable protective membrane, building paper appeared to be slightly more water-resistant than the plastic membrane assessed in this test; but neither of them showed adequate moisture protection during the outdoor exposure test. In field these products are only recommended for use as a temporary protection measure when more advanced methods are not possible. The building paper or plastic membrane may be pre-installed above NLT in the factory if the structural sheathing has to be installed at the site. Note a plastic membrane may make a horizontal work surface slippery and should be avoided on structures, such as a floor or a roof.

5. The vapour-impermeable membrane tested in this study provided the best water resistance and moisture protection for the NLT that was exposed to the exterior for about two months. For a roof structure the permanent roofing membrane should be utilized for on-site moisture protection. Installing an impermeable membrane on wet wood would eliminate moisture dissipation and must be avoided.

6. Space heating was confirmed to be effective for drying plywood, i.e., relatively thin products/assemblies. Severely wetted plywood sheathing, covered with a vapour-impermeable membrane on one side, dried under reversed temperature differential conditions. The most risky locations in the plywood reached a MC of around 20% within six weeks. However, heating was shown to be much less effective in drying NLT, i.e., large built-up members.

7. The core of a CLT reference specimen took weeks to gain elevated MC when exposed exterior; however, the subsequent drying was very slow. CLT also requires on-site protection in a wet climate to avoid moisture entrapment and accumulation.

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APPENDIX I   EXTRA INFORMATION ABOUT MOISTURE CONTENT MEASUREMENT

For measuring wood moisture content (MC), the resistance-based measurement tools available in North America, including the measurement system used in this study are primarily based on studies conducted by the US Forest Products Laboratory and FPInnovations (previously Forintek Canada Corp., and before that, as Eastern and Western Forest Products laboratories) (Pfaff and Garrahan 1984; James 1988; Garrahan 1988; FPL 2010; Onysko et al. 2010). For tools that had been originally calibrated for old-growth Douglas-fir, the research conducted by FPInnovations enabled reasonably reliable corrections for a range of wood species and temperatures (Pfaff and Garrahan 1984; Garrahan 1988). The average error involved for a clear material of an identified species is in the order of ±0.5% MC, although individual MC readings may be as much as ±2.0% different from the oven-dry values. In general the wetter the wood is, the lower its electrical resistance. When the MC is above the fibre saturation point (i.e., 30%), the liquid water in cell lumens has little additional contribution to the electrical resistance being measured. Therefore a MC reading above 30% typically indicates a larger degree of error. The measurement system showed an upper limit of 45% for lodgepole pine in this study. In the opposite extreme, when the wood is too dry, the electrical resistance becomes too high to be accurately measured. The lower limit of MC measurement turned out to be about 9% for Douglas-fir and 11% for lodgepole pine. Different wood species have slightly different relationships between electrical resistance and MC resulting from differences in density and chemical compositions. In addition, temperature is also a factor for a given wood species and a MC. Calibration has been started in the FPInnovations laboratory for a range of measurement tools including the system used in this study.

# APPENDIX II ENVIRONMENTAL CONDITIONS DURING TEST
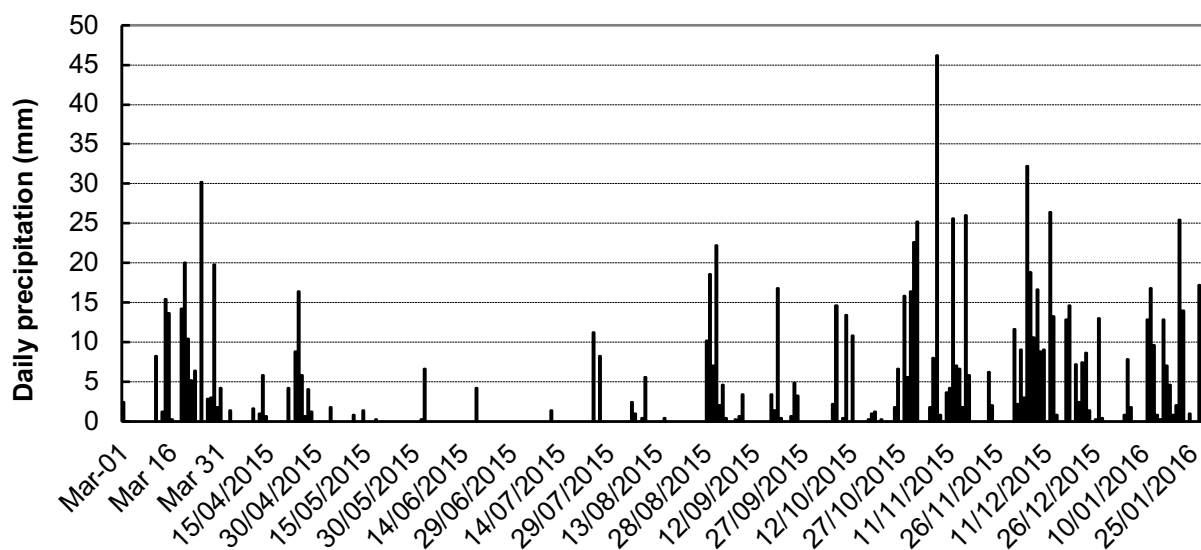
App-Figure 1   Daily precipitation during outdoor exposure from March to November, 2015[3]

App-Table 1   Monthly Rainy Days and Precipitation Amounts

Month	Rainy days (day)	Precipitation amount (mm)
2015, March	15	159
April	11	51
May	4	4
June	3	11
July	3	21
August	8	68
September	13	42
October	15	113
November	14	171
December	23	230
2016, January	21	167
Total	**130**	**1037**

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[3] Climate data was downloaded from Environment Canada: http://climate.weather.gc.ca/ for the station of the Vancouver International Airport.
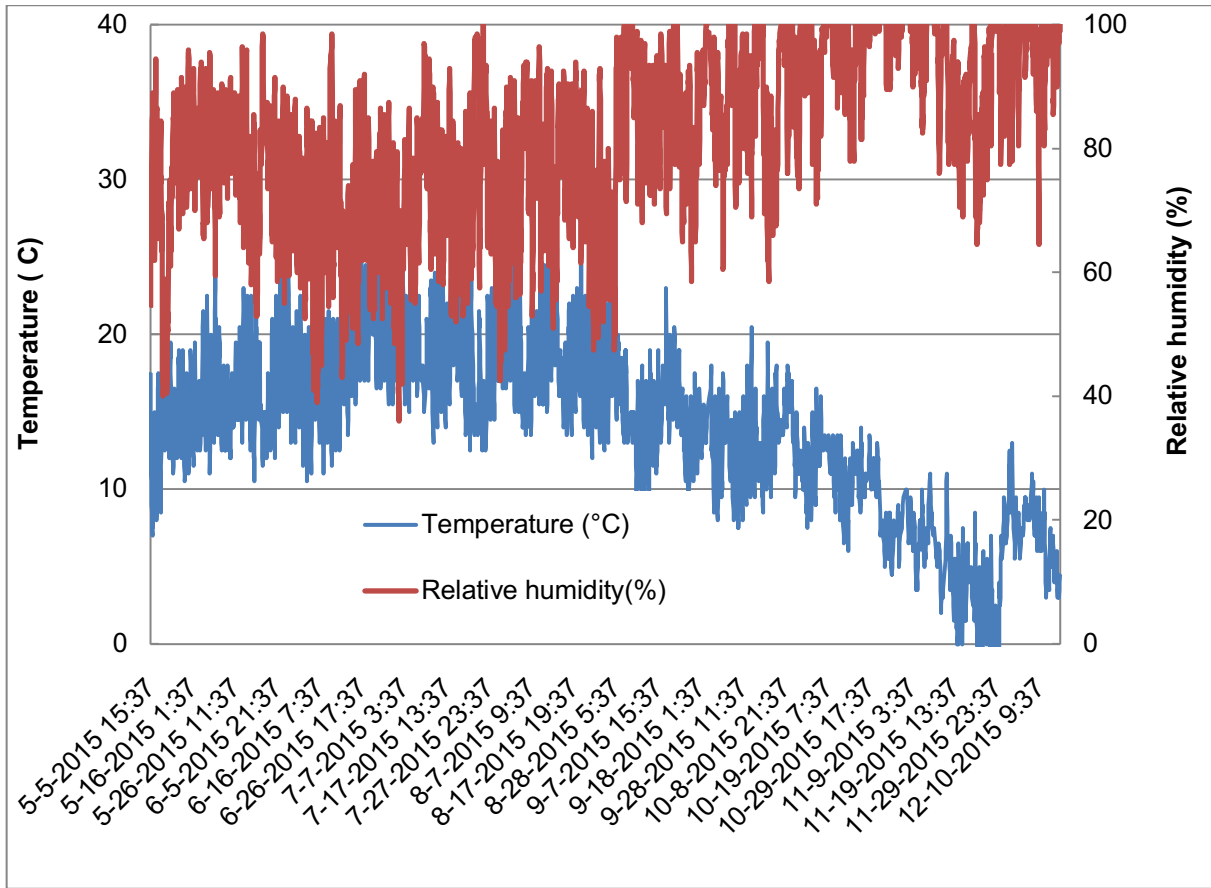
App-Figure 2   **Relative humidity and temperature recorded by HOBO under sheltered exterior conditions**
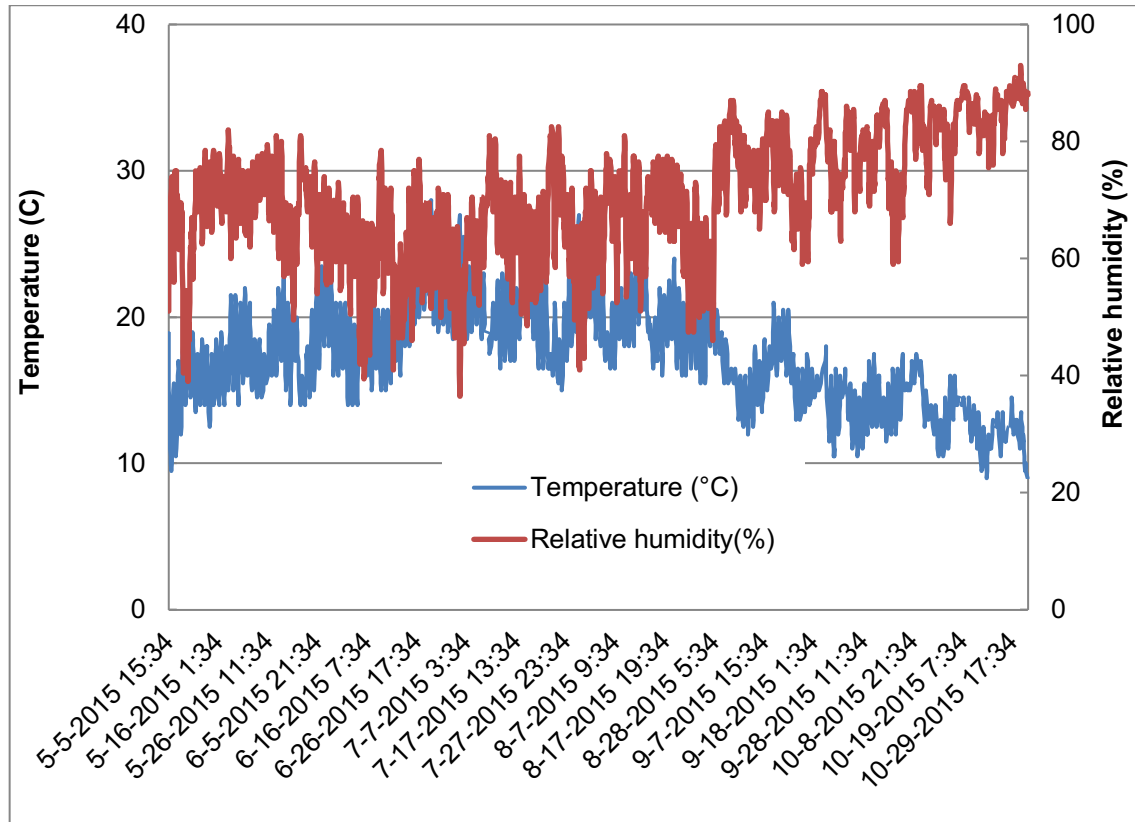
App-Figure 3   Relative humidity and temperature recorded by HOBO in the shed
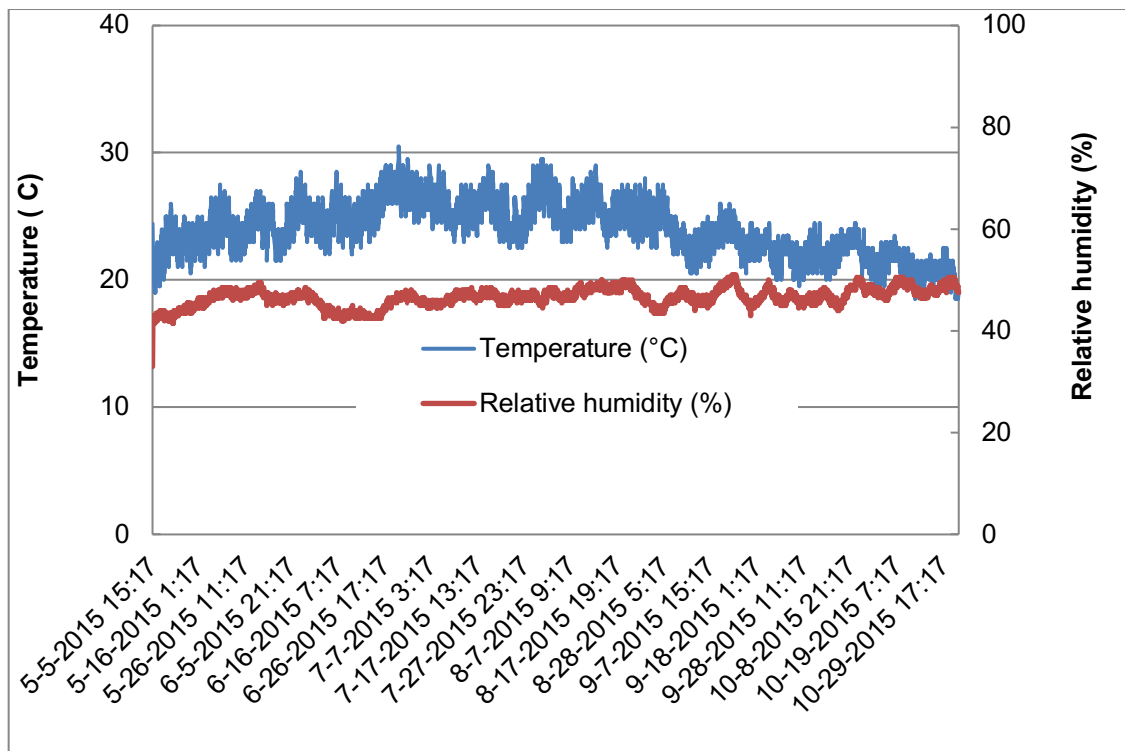
App-Figure 4   Relative humidity and temperature recorded by HOBO in the B1 box

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