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Assessing the application rate for an equivalent volume of boron-rod-treated Eastern black spruce (Picea mariana var. Mariana) species into five-layer cross-laminated timber (CLT) structures by Near-Infrared (NIR) Spectroscopy

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Assessing the application rate for an equivalent volume of boron-rod-treated Eastern black spruce (*Picea mariana* var. *Mariana*) species into five-layer cross-laminated timber (CLT) structures by Near-Infrared (NIR) Spectroscopy

Abstract

The rate of application of preservative substances in structured mass timber material is crucial for evaluating their effectiveness under long-term durability exposures. The potential of near-infrared (NIR) spectroscopy was assessed for the application rate of active ingredients through an equivalent volume of borate-impregnated preservative into Eastern black spruce *(Picea mariana* var. *Mariana)* species, engineered into five-layer cross-laminated timber (CLT) systems that were rewetted at a fixed moisture content (MC) approaching 80% for establishing a long-term durability function. Eastern black spruce five-layer CLT systems were inserted with boron rods throughout the central profile of sampled structures at a depth of 150mm ($5^{29/32}$inches) crosswise to the longitudinal grain direction for a varying inoculation period, ranging from 1 to 6 months. Evaluation of borate's diffusion gradient in terms of percent boric acid equivalent (%BAE) and percent borate penetration depths (%borate coverage), as well as the equivalent volume of treated wood (m^3) was considered the rate of application for boron rods in terms of a kilogram (kg) of boric acid equivalent per cubic meter of treated wood or equivalent board feet at a fixed conditioning period. This was performed for each sectional Eastern black spruce CLT element, which consists of five glued components of *lamellae* grouped in orthogonal orientations, alternately at a typical 90-degree angle, one *lamella* to another neighboring *lamella*. Borate diffusion tended to increase for duration treatments within 6 months, reaching a maximum threshold of $7.4E^{-02}$ m^3 equivalent volume of treated wood, such corresponding to a rate of application of 0.44 kg/m^3 or 31.37 board feet at the 6^{th} month of experimental duration. Computation of statistical prediction models based on boron rod validation yielded root mean square error (RMSE) values ranging from 0.7548 to 0.7017% and $5.62E^{-04}$ to $5.8E^{-04}$ m^3, while R^2 values were 0.58 and 0.54 for boric acid equivalent (BAE) and equivalent volume of treated wood, respectively. In this study, the potential of NIR Spectroscopy coupled with multivariate data analysis, using projection to latent structures (PLS) regression techniques, was utilized to show probable predictive abilities for estimating the rate of equivalent volume of wood-boron rods injected across the longitudinal grain direction throughout the central profile of five-layer Eastern black spruce *(Picea mariana* var. *Mariana)* cross-laminated timber concepts.

Keywords: Rate of application of borate distribution and equivalent volume of treated wood into five-layer cross-laminated timber, Boron rods injection treatment, NIR Spectroscopy, Eastern black spruce (*Picea mariana* var. *Mariana*) species.

Introduction

Widespread use of mass timber structures involving framed timber gridshells and the cross-laminated timber (CLT) concept has impressively increased over the previous decades, varying in terms of building type complexity and architectural diversification. This includes the economic and aesthetic aspects of CLT systems that are implicitly involved in showcasing the wood-using industry for building construction, as mass timber systems have received a worldwide array of impressive improvements (Koumbi-Mounanga et al. 2008; Brandner et al. 2016; Shu et al. 2026). While a few underlying themes remain omnipresent, such as the durability of the innovatively engineered mass timber structures and their remedial treatments for long-term exposures. However, comprehensive studies on protective treatments of mass timber buildings illustrate how to solve and prevent eventual issues related to rewetting mass timber structures, as well as to track all kinds of deterioration concerning the preservative ingredient efficacy while maintaining long-term durability performance. Hence, practical solutions are offered through preventive and preservative treatments, such as boron rods applied by injection into mass timber systems for newer construction or renovation projects (Blow and Summers, 1985; Lloyd et al. 1999; Lebow et al. 2010). Boron rod treatment by an injection process is one of the most simplified techniques that utilizes borate ingredients in their solid stick form, constituting an excellent fire retardant, while also being safe, efficient, and economically and environmentally sustainable. This preservative formula can delve into the borate diffusion in the different structural zones of the engineered wood products (Thevenon and Pizzi, 2003; Freitag and Morrell, 2005; Koumbi-Mounanga 2008 and 2015). In case the engineered wood structure becomes internally wet and vulnerable to decay attacks, boron rods in solid stick injections can be easily applied *in situ* as a remedial, preventive, and preservative treatment in response to observed moisture penetration or biological deterioration due to internal decay infection. Also, boron rod treatments offer the possibility of studying and understanding the specifications that chemically influence borate movements through the unique attributes of the woodblock structures. Hence, evaluating the rate of application of borate ingredients in terms of equivalent volume of treated wood, preservative penetration depth, and retention in the wood could potentially be a key result of studying the economic demonstration of structural wood products for preventative and preservative industrial operations (Morrell et al. 1990; Drysdale 1994; Rhatigan et al. 2002).

For statistics and chemometrics, analytical wet chemistry methodologies used to monitor the preservative ingredients (e.g., to examine the distribution of chemical compounds and comprehend the retention for effectiveness) in treated wood are, in most cases, either qualitative approaches or require quantitative methods to complement assessment, as quantifying techniques are destructive and time-consuming. This is true for wood specimens to be adjusted through conditional dimensions to fit the calibration requirements of the analytical devices. For example, quantifying assays in electron microscopy of materials, colorimetric and potentiometric titration techniques, as well as for other measuring instruments, such as inductively coupled plasma emission spectroscopy (ICPES), or ICP mass spectroscopy/spectrophotometric (MS) analysis (Awoyemi et al. 2009; Saadat 2012; Watanabe et al. 2011; Koumbi-Mounanga et al. 2015a). Exceptions were shown in the studies of Taylor and Lloyd (2007), Leblon et al. (2013), and Koumbi-Mounanga et al. (2015b), which utilized a non-destructive technique, such as near-infrared spectroscopy (NIRS) coupled with multivariate statistical analysis, to investigate specifications (moisture content and density) related to treated wood with preservative ingredients. In some alternative cases, Schwanninger et al. (2011) and Meder et al. (2002) have used NIRS to predict stiffness and adhesive bond strength of wood products. Henceforth, wide spectrum association studies by Burns and Ciurczak (2008), Koumbi-Mounanga et al. (2015c, 2016 and 2018), and Tsuchikawa and Shwanninger (2013) demonstrated the use of predictive approaches to answer questions related to collective or individual behavior, which model the effect of adhesive, surface colors, and contact angles of wood materials. In other research areas of study, NIRS has been used to predict wood strengths, mechanical properties, and quality assurance related to the chemical composition of wood products to create a spark vision for the wood-building industry by enabling and supporting natural sciences (Thygesen and Lundqvist 2000; Stirling 2013; Koumbi-Mounanga et al. 2012, and 2013), but no investigations have yet been conducted to examine the application rate of chemical preservative ingredients for an equivalent volume of treated wood in sectional cross-laminated timber (CLT) configurations.

In this proposed study, the potential of near-infrared spectroscopy (NIRS) was weighed for the estimation of application rate related to an equivalent volume of borate-treated wood (involving borate distribution and content) in small-scale sectional cross-laminated timber (CLT)-5-layer structures of Eastern black spruce (*Picea mariana* var. *mariana*) species. The engineered Eastern black spruce small-scale 5-layer CLT systems were rewetted to a fixed 80 percent moisture content to optimize preservative diffusion and impregnability treatment, using an injection technique with boron rods

throughout the central pieces of the Eastern black spruce CLT profiles, specifically at a depth of approximately 150 mm (5 $^{29/32}$ inches) crosswise to the longitudinal grain direction. This was carried out at different conditioning durations ranging from 1 to 6 months; hence, woodblock (small-scale Eastern black spruce CLT 5 layers) concepts were sawn orthogonally (at dry service conditions through 90 degrees following flat radial grain direction surfaces, and at standard room temperature) into sectional log materials before proceeding with indoor laboratory screening analysis. The application rate of preservative formulation for equivalent volume of treated wood was assessed by the potential of NIR screening analysis of the borate penetration depths in the established Eastern black spruce-element CLT profiles over the conditioned period to distinguish the untreated and treated-borate wood portions from parallelepipedal prisms and rectangular surface areas described through radial, tangential, and longitudinal grain directional axes of the wood edges. While thickness dimensions were related to the boron-based preservative retained in Eastern black spruce-element CLT surface areas (boron content in wood), which were determined by ICP-MS measurements in accordance with the American Wood Preservers Association (AWPA) standard A21-00 (2000). This allows for the estimation of the application rate from sourced boron rod preservatives in terms of kilogram (kg) of boric acid equivalent per cubic meter of treated wood or equivalent board feet using a fixed moisture content, as well as a fixed conditioning experimental period at room temperature as described the derived method in Richards et al. (1964). The resulting data were correlated to NIRS through multivariate screening analysis using projection to latent structures or partial least squares (PLS) regression models. Our investigation may help engineer an easy-to-operate, real-time sensor for continuous artificial intelligence (AI) monitoring, including on-site checks of key analytes relevant to environmental testing scenarios, particularly for diffusing preservative ingredients in mass timber structures to control and improve durability in wood-building operations, and training AI effectively.

Materials and Methods

For experimental design procedures, an Eastern black spruce (*Picea mariana* var. *Mariana*) species was selected among Canadian lumber species known for similar strength and stiffness characteristics, in accordance with the sixth edition of Canadian Standards Association (CSA) O177-(2023) and Standards 086-(1970), which supersedes the previous editions, published between 1965 and 2006.

Scale-up from Eastern black spruce lumbers to laboratory screening experimental sampling

About 40 units of Eastern black spruce (*Picea mariana* var. *Mariana*) lumbers with standard manufacturing dimensions of 12 board feet measuring 580mm (width) x 101.6mm (thickness) x 5.49m (length) or 2-inch (radial) x 4-inch (tangential) x 18-foot (longitudinal) pieces of nominal sizes were chosen for their high-grade surface appearance, avoiding knots, splits, pitch pockets, and other open defects.

-Conditioning for small-scale Eastern black spruce cross-laminated timber conception

Eastern black spruce lumbers were acquired green from a local lumber supply store (Ontario, Canada) and conditioned for experimental indoor laboratory screen assessments at room temperature (23.5°C), air-dry service condition (at least 48h) until the equilibrium moisture content ranged from 10 to 15% before machining (Koch 1972).

-Sawing for small-scale Eastern black spruce cross-laminated timber configuration

To simplify design conception in laboratory conditions and facilitate the better utilization of available materials, about 240 Eastern black spruce wood pieces measuring 85mm (width) x35mm (thickness) x250mm (length) sizes or 3 $^{11/32}$ inches (radial) x 1 $^{3/8}$ inches (tangential) x 9 $^{27/32}$ inches (longitudinal) grain directions of nominal sizes were machined through a Power bandsaw instrument, at room temperature, which were generated throughout a perpendicular cut crosswise longitudinal grain direction at 90 degrees to the free vibration angle of the cutting edge made with the flat radial grain surface to be assembled for lamination (Kang et al. 2024 and 2025).

-Gluing and manufacturing for small-scale Eastern black spruce cross-laminated timber structuration

Eastern black spruce wood pieces were superficially planed using an industrial wood planer machine before being grouped in a three-by-three disposal arrangement in five layers, while being crosswise bonded side-wise at typically 90 degrees on their three-by-three face grain surfaces with a liquid

resole phenol-formaldehyde (PF) resin (5% w/w applied upon surface) as described by Christiansen (1991). Whose PF manufacturer's recommendations around the 2011-2013 period were described by Momentive Specialty Chemicals (formerly Hexion). The assembled woodblock samples resulted in small-scale prefabricated Eastern black spruce cross-laminated timber (CLT) configurations harboring five (5) layers of lamination glued together as schematically designed in the **Fig. 1a**. To consolidated consistency of several layers of lamellae stacked crosswise (at 90 degrees) and durably glued together on their wide grain faces, the small-scale Eastern black spruce cross-laminated timber (CLT) concepts were laid-up under a pressing machine (PressMan, type ARC 450, Ontario, Canada) operator, assisted with a Press control system settled at 150 Bar during 30 minutes at ambient temperature (23.5 °C).

-Describing small-scale Eastern black spruce CLT 5-layer profile

A description of a perpendicular view of small-scale Eastern black spruce cross-sectional CLT structures profiled five glued layers with the following specificities:

- at the very upper and bottom layers of Eastern black spruce CLT profiles was defined with wood grain directional (radial/tangential) transverses, hereafter called “Transverse top and bottom sides";

-the two under layers were profiled with longitudinal grain directions, one located at the top and the other at the bottom of the centre core profile, hereafter called "Longitudinal top and bottom sides";

-and the central zone defined the core or centre transverse, which was precisely the location where boron rods should be inserted crosswise longitudinal grain into the Eastern black spruce CLT 5-layer system as schematically represented in **Fig. 1.**

A total of sixteen CLT 5-layer structures were surface machined at room temperature to actual sizes measuring 180mm (width) x250mm (thickness) x250mm (length) or 7 $^{5/64}$ inches (radial) x 9 $^{27/32}$ inches (tangential) x 9 $^{27/32}$ inches (longitudinal) for experimental laboratory conditions as represented in **Fig.1.**

- Conditioning for Eastern black spruce 5-layer CLT injection process with boron rods

A full-cell treatment procedure was carried out on the Eastern black spruce CLT 5-layer materials to adjust their moisture content to a fixed level of about 80% MC before the injection of boron preservative for all inoculating periods. Eastern black spruce CLT 5-layer materials were kept in a

conditioning (laboratory dry service) chamber at 15 °C with a relative humidity (RH) of > 15% to initiate the full-cell treatment process using double-distilled water solutions, which was part of the conditioning injection procedure. This was settled until the entire woodblock system reached the target moisture content (MC) above the fiber saturation point, ranging from 80 to 85%, using a vacuum pressure process cylinder in accordance with the AWPA Standard A02-05 (2005). The program was undertaken in a controlled system cylinder, which was settled at 11kPa absolute pressure using vacuuming through a total cycle treatment of 30min, overnight (24 h) pressurizing at 700kPa, including a final vacuum at 11kPa for 15min to condition the surface as suggested by the AWPA Standard A03-05 (2006).

The Eastern black spruce rewetted CLT 5-layer materials were rested for 24 hours at 50°C in a Dryteck Klin (USA, series 3900MC) chamber before calibrating with insertion holes, conditioning as described in Koumbi-Mounanga et al. (2025). About a dozen Eastern black spruce 5-layer CLT structures with their MC approaching 80% were drilled with depth holes around 150- 160 mm ($5^{29/32}$ – 6 $^{19/64}$ inches) diameters orthogonally to the cross-section of longitudinal grain through their central profiles (**Fig.1a** and **1b**).

For an effective installation, the boron rods were utilised as solid sticks of 8mm or $^{5/16}$ inch (diameter), 55mm or 2 $^{11/64}$ (length), and 6.5 grams (weight). Boron rod solid formulation contained an active ingredient concentration ranging from 60 to 90% disodium octaborate tetrahydrate (DOT) or $Na_2B_8O_{13}$ $4H_2O$, as the physical and chemical properties, including characteristic recommendations, are commercially available from Sasco Products Limited (Dartmouth, Nova Scotia, Canada).

The boron rod solid sticks were approximately inserted at a depth of 150mm (5 $^{29/32}$ inches), then capped with sealing wood sawdust into the Eastern black spruce sample's pre-drilled holes. All Eastern black spruce structured CLT 5-layer materials were wrapped in black plastic bags to minimize drying and external environmental influences during the inoculating investigation. Eastern black spruce CLT 5-layer specimens were stored at 23.5 °C within a relative humidity of about 85% in a Drytech Kiln (USA series 3900MC) chamber. We noted that some Eastern black spruce CLT 5-layer specimens (approximately four structured woodblock samples) were left as untreated controls and were not subjected to boron rod solid stick injection. The rest of the Eastern black spruce CLT 5-layer samples were conditioned for different periods, starting at 1-, 2-, 3-, and 6-month intervals, with three replicates per cycle.

To analyze borate diffusion (distribution depth, content, and equivalent volume of treated wood) and correlate it with NIR scan measurements, Eastern black spruce CLT 5-layer structures were perpendicularly sawn into six small-structured log sections. While being sliced crosswise throughout the width of the central longitudinal grain directions as well as the edges of the woodblock profiles at 90-degree angles of the flat grain surfaces and the cutting edges at room (23.5 °C) temperature. This process generated three small-scale Eastern black spruce log materials from each part of the boron rod installation with actual measurement sizes of 30mm (thickness) or 1 $^{3/16}$ inches (radial), 180mm (width) or 7 $^{5/64}$ inches (tangential), 250mm (length) or 9 $^{27/32}$ inches (longitudinal), starting halfway from the central portion of Eastern black spruce 5-layer CLT structures until the edges as represented in **Fig.1b** and **1c.**

Setting for NIR spectral measurements of 5-layer Eastern black spruce CLT borate-treated materials

Sliced Eastern black spruce log materials from 5-layer CLT structures were kept in conditioned storage at an ambient temperature (23.5°C) in a chamber under drying service conditions (relative humidity [RH] >15%) before scanning. NIR reflectance spectral data were acquired from parallelepipedal prisms through rectangular surfaces implied by split facial and backside sections of small-scale Eastern black spruce CLT 5-element log profiles, starting from the top rectangular areas to the bottom portion of the specimen, with a special focus on the borate injection zone at 2 min intervals using an Ocean Optics Inc NIR256-2.5-[HL-2000-HP-RS232] Vis-Near-infrared Spectrometer. The NIR (256-2.5) Spectrometer was equipped with a USB2000 UV-VIS (Ocean Optics Inc., 830 Douglas Ave, Dunedin, FL 34698, USA) device, including an optical probe positioned on the top of the small-scale Eastern black spruce CLT log sample at a 2mm diameter beam, using a spectral resolution of 5 nm and manual calibration for white/dark after triplicate measurements as described in Koumbi-Mounanga et al. (2026). The scanning process was applied three times at randomly selected spots over rectangular areas of small-scale Eastern black spruce CLT log materials on both the top and bottom surfaces, particularly on flat zones where the treatment was involved, including the glue line zonation that bordered the Eastern black spruce CLT 5 elements as described in Cooper et al. (2011).

Estimation following the surficial geometry similarity of parallelepipedal shapes of penetration, retention, and equivalent volume of small-scale Eastern black spruce CLT borate-treated materials

Following the conditioning time frame (1, 2, 3, and 6 months) allocated above, Eastern black spruce CLT 5-layer samples were processed for experimental screening examination (penetration depth, retention, and equivalent rate related to the volume of borate-treated wood) after their surface were scanned.

- Sampling for 5-layer Eastern black spruce CLT borate-treated analysis

Borate penetration depths of surficial areas were revealed over the Eastern black spruce CLT 5 lamellae by spraying a curcumin reagent formulation, which was made with about 0.25g curcumin in 10 mL concentrated hydrochloric acid and 10g salicylic acid in 100ml ethanol, as described in Williams 1968. This was applied to the split surfaces of three replicates of Eastern black spruce CLT materials sampled from both the face and back-side sections. Special attention was given to the red/pink colorations that were developed at a concentration of borate-curcumin reagent equivalent to more than 0.02% boric acid reagent, as described in the study of Murphy and Tuner 1989, while the duration for revealing ranged from 5 to 20 minutes. Hence, untreated wood zones were pale yellow, as represented for all conditioned periods on facial and back-side regions in **Fig. 2** at 1-month (**Fig.2a)**, 2-month (**Fig.2b)**, 3-month (**Fig.2c)**, and 6-month **(Fig.2d)** treatment periods. Borate surficial coverage and penetration depths were undertaken after the sprayed reagent over the Eastern black spruce 5-layer CLT log surfaces were completely dried at room temperature and RH >15%.

-Measuring borate surficial coverage and penetration depth in Eastern black spruce five-layer CLT profiles

Measurements of the dried-untreated (yellow) and treated (pink/red) dashed zones were established in triplicate to examine borate penetration depth on surficial rectangular areas, as described above, over the different Eastern black spruce layers in CLT systems using a digital numerical tape (Vernier caliper Precise) instrument with a resolution of around 5% absolute error.

The three replications of tape measurements were conducted specifically on the revealed expressive (red/pink/yellow) colored spots of parallelepipedal Eastern black spruce prisms in conditioned dry services at ambient temperature (23.5 °C) for a relative humidity [RH] >15%. This was implied by the simplified ratio formulas presented hereafter in accordance with the AWPA A3-91 standard (1991), in which the summarization of the data was represented in **Fig. 3** using different log sections from the face (**Fig.3a** of log1), (**Fig.3b** of log2), and (**Fig.3c** of log3), as well as the back sides (**Fig.3d** of log1), (**Fig.3e** of log2), and (**Fig.3f** of log3).

Thus, penetration depth in percent (%) equals the ratio of the sum of triplicate tape measurements carried out over treated Eastern black spruce areas as described by the equation below:

$$\boldsymbol{Penetration\ depth}(\%) \quad = \sum_{k=0}^{n} \binom{n}{k} \left(\frac{\boldsymbol{Measurements\ of\ treated\ zone}}{\boldsymbol{Dimensions\ of\ wood\ (l,w\ or\ h)\ edge\ to\ be\ treated}}\right) \quad \mathbf{100}^{n-k}$$

Where: (k) was referred to moisture-, pressure-, and temperature-dependent via the Arrhenius constant approach; (n) was referred to the number of duplicated orders that was determined experimentally for three replications; and (l, w, or h) were related to wood directional edges of longitudinal (l), radial (w) or tangential (h) according to parallelepipedal prisms in Eastern black spruce 5-layer CLT profiles.

To estimate boron retention in sliced wood zones, a complementary study was conducted over randomly selected areas that were ground to wood sawdust samples (approximately 0.5g) collected from Eastern black spruce CLT surfaces to be analyzed by ICP-Mass Spectroscopy, including a (+/-) 0.05 absolute error.

-Eastern black spruce sampling for gradient of borate diffusion analysis

The gradient of the borate diffusion method was carried out by analyzing thin-sliced Eastern black spruce wood pieces, which were obtained from the surficial top to bottom of Eastern black spruce CLT log materials, split at a 90-degree angle by the cutting bandsaw machine and edges of the wood, through perpendicular sawing every 0.5cm ($^{13/64}$ inch), starting from the exposed sides to the backside surfaces. This was generated accordingly for one surficial log portion, thin Eastern black spruce wood pieces with dimensions described as follows: 9 transverse areas of actual sizes about 85mm (width) x35mm (thickness) x5mm (length) or 3 $^{11/32}$ inches (radial) x 1 $^{3/8}$ inches (tangential) x $^{3/16}$-inch (longitudinal) samples and 2 longitudinal segments of 5mm (width) x35mm (thickness) x250mm

(length) or $^{3/16}$-inch (radial) x 1 $^{3/8}$ inches (tangential) x 9 $^{27/32}$ inches (longitudinal) specimens to be analyzed independently.

- Measuring borate retention/concentration of 5-layer Eastern black spruce CLT materials

Sliced Eastern black spruce materials were ground into powder with a Thomas-Wiley laboratory mill grinder (USA model 4) and screened with a 2mm mesh Tyler equivalent filter (USA series equivalent No. 18). A volumetric borate measurement was conducted through an extraction process from 0.5g of sampled sawdust in 40 mL of hot (90°C) distilled water for 4 h in a Blue *M* water bath (USA model MW1165C-Serial No. M71211). The extracted formulation was diluted 50 times, resulting in a final volume of approximately 250 mL. The results were finally analyzed by ICP-Mass Spectroscopy to be expressed as concentrations of Eastern black spruce surface coverage of borate-treated (e.g., mg/mL) and then converted to the mass of borate solution by mass of borate solute parts per million (ppm), as described in Koumbi-Mounanga et al. (2020), using the ratio equation formulas below:

$$\text{Concentration} = \frac{\text{mass of solute}}{\text{volume of solution}} \text{(e.g., mg/mL)}$$

When normalized to parts per million (ppm):

$$\text{ppm} = \frac{\text{mass of solute}}{\text{mass of solution}} \times 10^6$$

Thus, the concentrations of elemental boron measured by ICP (-OES or -MS) x [(Molar mass of boric acid (H_3BO_3), approximately 61.83 g/mol) ÷ (Molar mass of elemental boron (B), approximately 10.81 g/mol)]. This was equivalent to the concentrations of H_3BO_3 applied with a conversion factor of approximately 5.72 (e.g., 61.83 ÷10.81), expressed in % boric acid equivalent in accordance with Cockcroft (1974).

- Measuring the equivalent volume of 5-layer Eastern black spruce CLT borate-treated materials

Equivalent volume (m^3) of borate-treated wood was calculated based on the concept introduced previously, using parallelepipedal prisms defined on surficial Eastern black spruce CLT profiles. It was a familiar fact that the estimation of borate ingredients was based on rectangular surfaces of parallelepipedal prisms impregnated with preservatives. Knowing that parallelepipedal shapes were

described by the radial (R or w), tangential (T or h), and longitudinal (L) directional axes of the wood edges, the calculation formula was expressed as follows:

$$V = l \times w \times h$$

Where the volume of borate-treated wood was equal to the product of the measured dimensions of the revealed borate zones over radial (R or w in meters), tangential (T or h in meters), and longitudinal (L in meters). This included an (+/-) error deviation encountered in the T-test statistical estimations through three experimental repetitions; at the same time, resulting units were m^3 or converted to ft^3 to be correlated to percent (%) in a 100 mL solution of borate solute (volume/volume % (v/v %)) with the formula described below:

$$\frac{\text{mL of solute}}{\text{100 mL solution}} \times 100\%$$

Therefore, the equivalent volume in % corresponded to the total borate active ingredients that were rationalized to the targeted retention (i.e., if 100kg of preservative was used for a target retention of about 4 kg/m^3, so, to treat 25 m^3 of wood) in accordance with the AWPA Standard A19-93 (1996).

Estimating the application rate of the targeted equivalent volume of 5-layer Eastern black spruce CLT borate-treated materials

The application rate of borate preservative was estimated in accordance with a breakdown approach described by Waldron and Cooper (2010), who modeled simultaneous three-dimensional leaching and fixation of preservative ingredients in unfixed wood materials using partial differential equations combining the diffusion flow and reaction kinetics. By considering the amount of borate-treated ingredients applied to the Eastern black spruce CLT surfaces for fixed moisture content (80%) at room temperature (23.5 °C) and conditioning periods ranging from 1 to 6 months, the general rate formula was compacted as follows:

$$\boldsymbol{Rate\ of\ application\ (Uptake)^{\%} = \sum_{k=0}^{n} \binom{n}{k} \left(\frac{Weight\ after\ treatment\ - Weight\ before\ treament}{Volume\ of\ wood\ (l.\ w.h)\ treated}\right)^{k} 100^{n-k}}$$

Where: (k) for the constant related to moisture-, pressure-, and temperature-dependent conditions via the Arrhenius concept, (n) for the number of duplicated reaction orders, herewith determined experimentally to three replications, and (l, w or h) for the wood edges of longitudinal (l), radial (w)

or tangential (h) grain directions as defined by Eastern black spruce parallelepipedal CLT profiles with rectangular prisms.

However, the application rate (uptake), expressed in percent, was the ratio of the difference between the sampled weight after treatment and the sampled weight before treatment. Thus, data were expressed in kg/m^3 or converted to lb/ft^3, as in a similar derivative computation by Moussambi-Membetsi (2004), using the combined relation of spectroscopic approaches. Hence, all borate measurement data collected from Eastern black spruce 5-layer CLT materials were correlated with the scanned NIR spectra.

Data treatment for 5-layer Eastern black spruce CLT borate-treated materials

The Unscrambler 9.8 (CAMO Software Inc., 1 North Cir., Woodbridge, NJ 07095-2105, USA) was processed with the recorded data of NIR reflectance spectra, which were acquired in the wavelength 900-2400nm region and were smoothed by applying a second derivative 13-point Savitzky-Golay transformation. NIR Spectra were related to multivariate data analysis through the projection to latent structures or partial least squares (PLS) regression method of borate diffusion (penetration depth and boron-based preservative content, and equivalent volume of treated wood) obtained from Eastern black spruce scanned CLT samples. PLS regressions were computed with the concept of the Test set validation method, with an external recorded number of scans that were sufficient to be used for model development and to be classified as independent calibration and validation in the Unscrambler program. This includes a computation using two (2) factors (PCs) determined based on RMSEp values to give an optimal prediction for the modeling (Boulesteix and Strimmer 2006; Rosipal and Kramer 2006; Esbensen et al. 2002). Moreover, the performance of PLS-R models was calculated with relative percent difference (RPD) to estimate the ratio of the standard error of performance (SEP) to the standard deviation (SD) of the reference data as described by Geladi and Kowalski (1986).

Results and discussions

A stringent evaluation of preservative formulations by application rate was conducted according to incubation periods, using triplicate statistical chemometric analysis to determine the equivalent

volume uptake of active ingredients applied per treated wood-framed area. Hence, key measurements for calculating product weight were based on borate products retained over varying surficial wood zones, mostly at the limiting zones, whereas Eastern black spruce preservative-treated CLT frames were applied.

Application rate analysis for boron rod penetration depths in framed Eastern black spruce CLT systems

Fig.3 represents the averaged triplicate measurements of borate penetration depths operated on Eastern black spruce CLT 5-layer specimens at varying experimental conditioning periods over the different log sections from the facial **(Fig.3a** of log1**), (Fig.3b** of log2**),** and **(Fig.3c** of log3**)** profiles, as well as from the back sides **(Fig.3d** of log1**), (Fig.3e** of log2**),** and **(Fig.3f** of log3**)** profiles. When the Eastern black spruce CLT structure is impregnated with chemical preservative ingredients, specific properties, such as moisture content, internal temperatures, strength and stiffness of the members, may be modified over the experimental conditioning duration, and thus obtained depths of penetration that differ from the sourced boron rod installation to diffusing zonation around Eastern black spruce CLT members. Taylor et al. (2023) perceived, in a borate treatment investigation of Douglas-fir (*Pseudotsuga menziesii*), spruce (*Picea* spp.), and radiata pine (*Pinus radiata*) species, that CLT systems that were typically not properly treated were due in part to a lack of efficient knowledge of effective methods for treating large-mass structures into standard cylinder dimensions, as well as a lack of information on how to handle them. In contrast, a controlled application rate technique using slow-diffusing procedures in CLT systems may overcome these obstacles; however, over time, it might induce changes in specifications such as mechanical properties and wetting resistance due to swelling and shrinkage related to environmental exposure actions. The selected preservative treatment and techniques should effectively penetrate cracks in CLT members and glue/bond line (adhesive joint between adjacent lamellae) regions, as observed by Colak and Colakoglu (2004).

Thus, it can be observed from the facial (**Fig.3a** of log1), (**Fig.3b** of log2), and (**Fig.3c** of log3) profiles that, at room temperature and fixed moisture content, based on treatment durations ranging from 1 to 6 months, the penetration depth was mostly located around the source boron rod injection areas that were characterized by more diffusing (red/pink) coloration. Indeed, borate diffusion started from the closest areas of boron rod insertions, revealing a higher intensity of curcumin reagent action on the sprayed

surfaces of Eastern black spruce CLT elements, whose chemical reaction involves a complex formed by boric acid, wood components, and active ingredients from the formulation-based curcumin (DDAC for didecyldimethylammoniun chloride and glycol chemical compounds), as observed in the studies of Piao et al. (2009) and Ren et al. (2026). Similar observations were obtained, especially in the wood core zones through the lengthwise central and radial directions of the wood edges within a 6-month conditioning duration, which revealed the same trend of borate diffusion (penetration depth) from sectional log # 1 to 3, proportional to conditioning duration, as presented in **Fig.3** from (**Fig.3d** of log1), (**Fig.3e** of log2), and (**Fig.3f** of log3) back side profiles. Bagheri and coworkers (2022), based on screening laboratory exposures of small-scale Douglas-fir CLT systems, examined different borate uptake levels to model dip-treatment parameters, including the effects of adhesive on threshold consistency relevant to fire, termite, and decay tests.

In the same context, Lebow et al. (2013) studied the effect of concentration on the diffusion of boron in lumber-framed specimens at various moisture contents ranging from 18 to 21 percent during different conditioning periods (6, 13, and 26 weeks). They reported that higher concentrations linked to higher moisture contents produced greater penetration depths and yielded greater boron retention in the outer assay zone to protect against termites and decay fungi. As such was expected, that the significance of the increase in the mean %borate coverage was linked to treatment conditioning, which was more evident for the transverses (middle-sides) and both the longitudinal (top and bottom sides) grain directions, as represented in **Fig.3**. Hence, some differences could be observed like evidence of borate diffusion throughout the transverses (bottom-side) when comparing both the transverse (bottom/topsides) at a 6-month experimental duration due to wettability, as well as influences of hydroxyl groups of chemical constituents (Jordan and Wellons 1977; Mitsui et al. 2008).

The maximum mean percent of boron rod penetration depths was obtained for 70% borate coverage by considering the borate distribution over the backsides of log 3, as represented in **Fig.3**. However, additional experiments should be undertaken to include more specifications related, for example, to outdoor weathering exposures, as well as other influences concerning glue lines and cracks on borate migration. Berg et al. (2015) and Koumbi-Mounanga et al. (2015d) have previously shown that glue lines slightly influenced borate migration in CLT structures through experimental screening exposures. The first study examined how glued laminated timber's load-bearing capacity is influenced, while the second compared borate distribution in treated and untreated mass timber materials. This influence led

to shrinkage and swelling of the wood materials, thereby inducing stresses in Eastern black spruce CLT structures.

Application rate analysis for gradient of boron diffusion into Eastern black spruce 5-element CLT in function of inoculating durations

Figs. 4, 5, and **6, a** (Radial top-side), **b** (Longitudinal top-side), and **c** (Radial central-side), represent a summary of data results regarding the borate flow rate gradient by inoculation duration over upper radial, longitudinal, and radial central portions of Eastern black spruce CLT (log#1, 2, and 3) profiles. Lebow et al. (2005) examined the treatability of framing Spruce-Pine-Fir species, compared solution uptake and penetration of boron preservatives with similar-level ingredients, to note that the treatment used or the formulation applied were collapsed differently to prevent attack by decay fungi and insects. **Figs. 4, 5,** and **6, d** (Longitudinal bottom-side) and **e** (Radial bottom-side), also, summarize the collection of measurements related to the borate application rate gradient as a function of inoculation durations (1, 3, and 6 months) of the Eastern black spruce CLT (#log1, 2, and 3) five lamellae. Mankowski et al. (2024) evaluated borate-treated Norway spruce and southern pine species in an above-ground protected test to extend service life and prevent biological attacks. They targeted the wood treatment with low levels of chemical protectants, using vacuum-applied disodium octaborate tetrahydrate (DOT) in a glycol solvent, which was suitable for manufacturing CLT panels.

Apart from the sliced Eastern Black spruce (logs #1, 2, and 3) areas closest to the treatment point, where concentrations tended to decrease with treatment duration, all the borate application rate gradients over the different lamellae showed a similar trend for all inoculation periods, ranging from 1 to 6 months (**Figs. 4, 5,** and **6**). This was attributed to atmospheric pressure, room temperature, and relative humidity, which progressively influenced borate migration as inoculation duration increased with the distance to be treated (Salman et al., 2014). Ra et al. (1999) examined the diffusion of boron through southern pine (Pinus spp.) at various moisture contents, temperatures, and treatment conditions along longitudinal grain directions, where the faster flow rate was recorded compared with the radial and tangential wood edges.

In addition, a comparison of borate application rate gradients in the transverse bottom and top sides within 6 months of the experimental duration (**Figs. 6)** revealed a real implication of the combined influence of intrinsic and extrinsic environmental factors related to internal structural wood materials

(Felix and Gatenholm 1991). This was hindered by several obstacles due to the specificity within the species or experimental conditions, explaining the unequal amount reported in Eastern black spruce CLT elements, which indirectly affected the diffusion gradient (Colakoglu et al. 2003).

We also noted that Eastern black spruce CLT (logs #1, 2, and 3) lamellae on the radial top sides showed no record of preservative ingredients, hypothetically due to different factors, such as orientation influences of directional grain edges when storing or disposing of specimens in horizontal/ vertical setup. Tsunoda (2001) studied a similar hypothesis in the treatability of Cryptomeria japonica D. Don sapwood structures with boron preservatives to be resistant to biotic agents, such as decay fungi and subterranean termites in laboratory bioassays. They concluded that permeability, wettability affinity, and the weight of formulation ingredients or gravity (heaviness) effects should be involved.

Evolution of the application rate for equivalent volumes of boron rod-treated 5-layer Eastern black spruce CLT log (#1, 2, and 3) materials

Fig.7. shows the evaluation of the application rate related to equivalent volumes (m^3) of treated Eastern black spruce CLT (log#1, 2, and 3) sections with borate ingredients as a function of treatment duration. The evolution of the borate application rate in Eastern black spruce 5-layer CLT volume-treated increased progressively with treatment inoculation periods, as all related statistical metrics for the evaluation are listed in **Table 1.** This showed that borate diffusion also depended on other influences, both intrinsic to the Eastern black spruce material (anisotropic, hygroscopic, heterogeneous) and extrinsic (temperature, moisture content, the density of the active ingredient) that were known to be revealed by characteristic features with high importance in borate migration (Obanda et al. 2008; Hans et al. 2013). Hence, similar observations were found in a study by Dirol (1988), who relied on moisture to carry the active ingredients of DOT deep into the wood fibers, as solid rods react passively like a reservoir that dissolves when sufficient moisture is present, requiring careful control.

Predicting the application rate for equivalent volumes of boron rod-treated 5-layer Eastern black spruce CLT materials

Fig. 8 shows the results of the prediction of borate diffusion in the Eastern black spruce five-layer CLT structures for variable triplicates of experimental durations. The details of the NIRS prediction of borate retention (%BAE) are presented in **Fig. 8a**, and the equivalent volumes (m^3) of treated wood in Eastern black spruce CLT structures are presented in **Fig. 8b.** In a large-scale example, An and Froese (2023) estimated the volume of standing trees using measurements of stem diameter and a comparative geometric formula for the terrestrial Light Detection and Ranging (LiDAR) accuracy, using water displacement in the scanned area. Hence, in a small-scale example, the equivalent volume of treated Eastern black spruce 5-layer CLT materials was modeled regardless of the trend of borate migration and movement from one segment to another compartment, with more pronounced variability related to the inoculation durations. The performance of the measured equivalent volume was linked to borate retention modelling in segmented Eastern black spruce CLT profiles, starting from the top to the bottom sides.

PLS models of %BAE and equivalent volume (m^3) of Eastern black spruce treated with both borate preservatives were able to provide reasonably good correlations (R^2) between calibration and validation retention values. These achieved values ranged from 0.533 to 0.611 for borate retention (%BAE) and 0.493 to 0.536 for equivalent volume (m^3) of treated 5-layer CLT systems and were statistically significant at *p*-value <0.0001. The related statistics of prediction (calibration/validation) were listed in **Table 2**. The R^2 values for prediction (calibration/validation) models were 0.573/0.58 for %BAE, and 0.688/0.543 for equivalent volume (m^3) of distributed borate preservative in Eastern black spruce CLT configurations. RMSE (calibration/validation) achieved 0.7548/0.7017% and 5.8E-04/5.61E-04m^3, respectively.

Thus, the use of average boron diffusion through directional wood edges was observed, with differences between real (calibration) and predicted (validation) data in the early stages of preservative diffusion, as expressed by De Groot et al. (2000) in an evaluation study concerning the distribution of borates around point-source injections in solid members of eastern cottonwood (*Populus deltoides* Bartr. Ex Marsh.), laminated beams of red maple (Acer rubrum L.), or Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) members exposed to the environment. However, modelling of the application rate of borate preservative showed a lower trace of borate concentration in the volume portion at the

555 bottom sides, compared to the top and center profiles of the Eastern black spruce specimens, due to the
556 placement of the boron rod formulation. Grace and Yamamoto (1994) conducted indoor laboratory and
557 field experiments to evaluate the effectiveness of sodium borate and disodium octaborate tetrahydrate
558 (DOT) formulations in preventing termite damage. They observed that, while multiple applications of
559 preservative ingredients used can be predicted through the treatment technique in wood specimen over
560 surficial levels to distinguish the treated and untreated zones, the preservative was not effectively
561 diffused into the heartwood of the Douglas-fir refractory species. Hence, Chen et al. (2024) evaluated
562 the combined effects of boric acid application rate (kg/m^3), heat modification for durability, and the
563 mechanical properties of Cunninghamia konishii plantation wood to improve termite resistance.
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565

Conclusions and recommendations

The present study aimed to assess the application rate of equivalent treated wood volumes using the potential of near-infrared spectroscopy (NIRS) for predicting borate diffusion (distribution and content) in cross-laminated timber (CLT) structured with 5 layers of Eastern black spruce (*Picea mariana* var. *Mariana*) species. Evaluation of borate application rate through volumetric treated layers was influenced differently by intrinsic and extrinsic environmental actions to explain the differences observed as a function of inoculation periods in Eastern black spruce CLT members, which were rewetted at a fixed 80 percent moisture content (MC) before boron rod injection in crosswise longitudinal grain directions. Thus, the borate application rate studied was revealed to be above the minimum level for pre-treatment and remedial protection of indoor mass timber specimens against biotic attacks, as we found an equivalent volume of treated wood of about $6.319^{e-02} m^3$ (2.2315 ft^3) for a threshold rate of preservative that was equivalent to 1.011^{e-02}kg of boric acid equivalent (BAE) per cubic meter of wood (0.0101 oz per cubic foot) within a 6-month inoculation period. Further developments of the experiment need to explore different species as well as other treatment methods, including other preservative formulations, using NIR Spectroscopy for analysis. We examined the application rate through borate flow estimation revealed by the potential of NIRS coupled with multivariate statistical breakdown, such as the projection to latent structures (PLS) regression technique, in the Eastern black spruce species. Such an approach is still empirical, and physics-based models need to be extended to explain the mechanistic factors implied by environmental stressors involved in mass timber structural materials, to eventually expand the study to outdoor exposures as well as to provide a comprehensive overview of the integration of AI-enhanced NIR technology into novel operational usage, herewith the example of being used in machine learning and manufacturing endeavours that are still to be industrialised.

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Figure legends

Fig.1. Examples of Eastern black spruce cross-laminated timber (CLT) materials: (a) 5-layer Eastern black spruce CLT schematically sampling with the direction of the boron rod inserted lengthwise along the grain of the central member profile, (b) overview of some replicate set Eastern black spruce samples prepared for borate analysis, and (c) top view of Eastern black spruce specimen profile splitting for borate analysis.

Fig.2. Illustrations of the facial and backside profiles of the different Eastern black spruce logs showing the borate coverage distribution at different conditioning periods for a fixed constant moisture content (80%).

Fig.3. Analysis of Borate coverage distribution (%) for different conditioning duration (1 to 6-month) at a constant moisture content: (a) Borate distribution from Eastern black spruce log 1, (b) Borate distribution from Eastern black spruce log 2, (c) Borate distribution from Eastern black spruce log 3, (d) Borate distribution from back-side of Eastern black spruce log 1, (e) Borate distribution from back-side of Eastern black spruce log 2, and (f) Borate distribution from back-side of Eastern black spruce log 3. For each probe, values sharing the same letter (α, β, γ, δ, ε, λ, μ) are not significantly different at the 5% level of confidence for Eastern black spruce estimation.

Fig.4. Estimation of the gradient of borate diffusion into Eastern black spruce CLT log materials for a 1-month treatment duration at a constant moisture content (80%). Each dot represents an average of 3 replicates.

Fig.5. Analysis of the gradient of borate diffusion into Eastern black spruce CLT log materials for a 3-month treatment duration at a constant moisture content (80%). Each dot represents an average of 3 replicate specimens.

Fig.6. Evaluation of the gradient of borate diffusion into Eastern black spruce CLT log materials for a 6-month treatment duration at a constant moisture content (80%). Each dot represents an average of 3 replications.

Fig.7. Examination of the application rate of borate diffusion into Eastern black spruce CLT logs 1, 2 & 3 as a function of treatment duration at a constant moisture content (80%). Each dot represents an average of 3 replicates.

Fig.8. Examination of the projection to latent structures or partial least squares (PLS) regression models of boron content diffusion: (a) prediction of boric acid equivalent (BAE in %) and (b) prediction of equivalent volume (m^3) of borate-distributed Eastern black spruce materials. Each dot represents an average of 3 Eastern black spruce NIR Spectra for calibration and validation.

Table

Table 1. Total estimation of statistics resuming the application rate estimation based on sum of 5-layer Eastern black spruce CLT configurations in function of conditioned periods.

	Conditionned period (months)			
	1	2	3	6
BAE (%)	4.109	5.759	7.41	12.133
Quantity of preservative used (kg)	0.163	0.191	0.209	0.253
Equivalent volume of treated Black spruce material (m^3)	4.087^{e-02}	4.785^{e-02}	5.2^{e-02}	6.319^{e-02}
Rate of application (kg/m^3)	6.54^{e-03}	7.66^{e-03}	8.38^{e-03}	1.011^{e-02}

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848 **Table 2.** Summarization of statistics resulting from the partial least squares or projection to latent
849 structures (PLS) regression of Eastern black spruce in **Figure 8**: (a) Calibration prediction and (b)
850 Validation prediction of boric acid equivalent (BAE in %) and equivalent volume (m^3) of treated
851 Eastern black spruce materials with borate distributed, respectively.

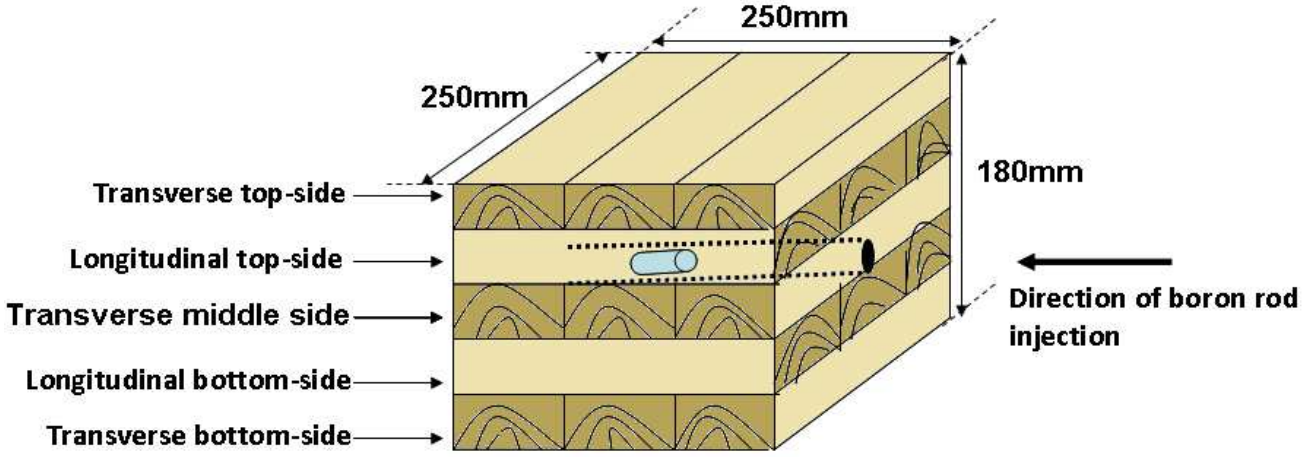
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	Slope	Intercept	RMSE	SE	Bias	r	*RPD*	*p-value*	n
BAE (%)									
a)	0.373	0.179	0.701	0.702	-1.27^{e-06}	0.611	1.6	0.0001	321
b)	0.334	0.195	0.755	0.756	4.60^{e-03}	0.533	1.5	0.0001	321
Equivalent volume of treated Black spruce material (m^3)									
a)	0.287	4.15^{e-04}	5.61^{e-04}	5.62^{e-04}	-9.52^{e-02}	0.536	1.5	0.0001	725
b)	0.267	4.28^{e-04}	5.8^{e-04}	5.8^{e-04}	2.19^{e-06}	0.493	1.4	0.0001	725

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871 **Figures**

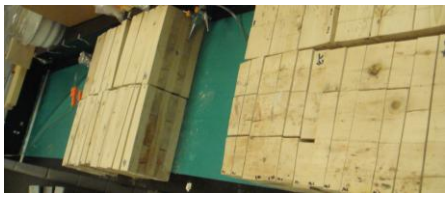
(a) Schematic of Eastern black spruce CLT (5 layers) rewetted at 80%MC and boron rod treated



(b) Sliced Eastern black spruce CLT structures for borate analysis



(c) Example of top Eastern black spruce 5-layer CLT profile samples for boron rod treatment



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873 **Fig.1**

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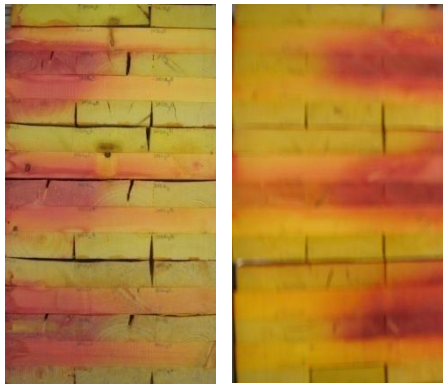
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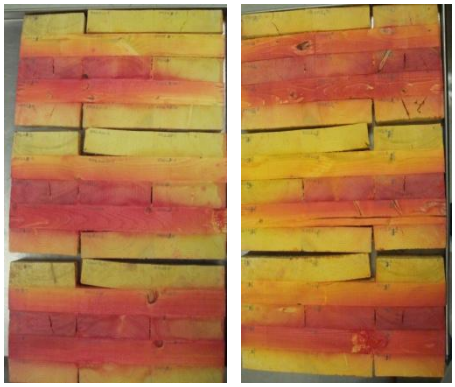
a) Facial and back-side Eastern black spruce section after 1 month incubation at 80%MC



(b) Facial and back-side Eastern black spruce section after 2 months incubation at 80%MC



(c) Facial and back-side Eastern black spruce section after 3 months incubation at 80%MC



(d) Facial and back-side Eastern black spruce section after 6 months incubation at 80%MC



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885 **Fig.2**

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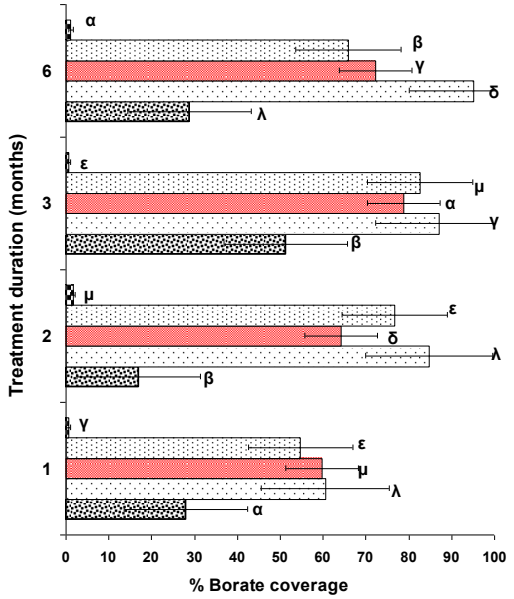
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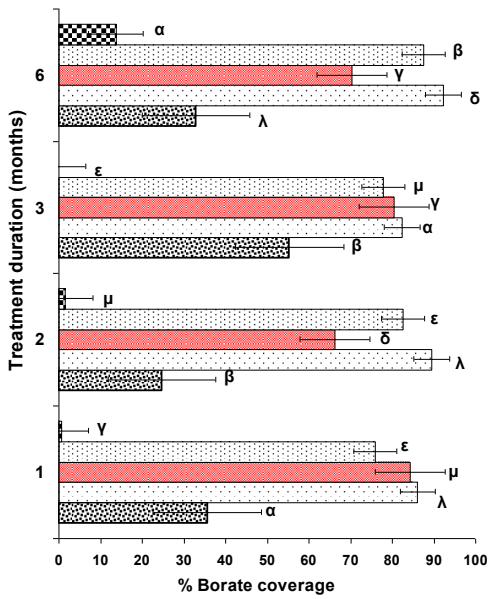
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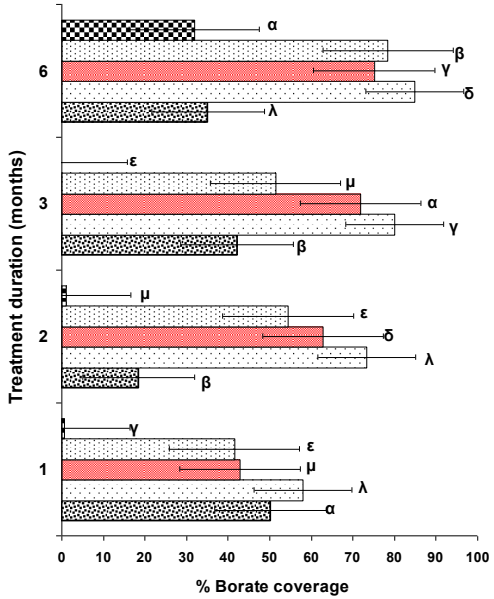
(a) Borate distribution in Black spruce log 1



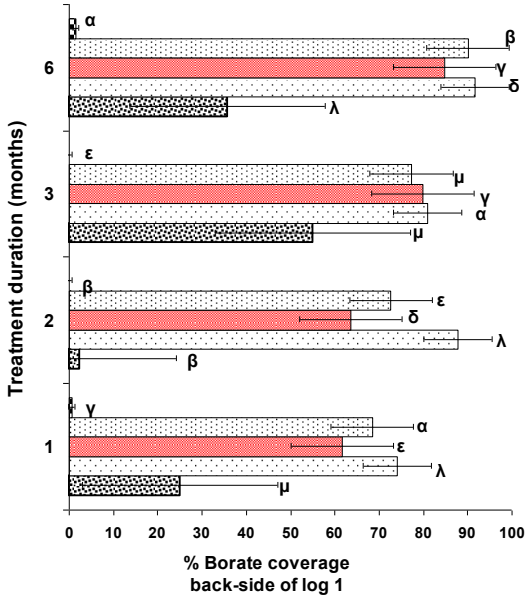
(b) Borate distribution in Black spruce log 2



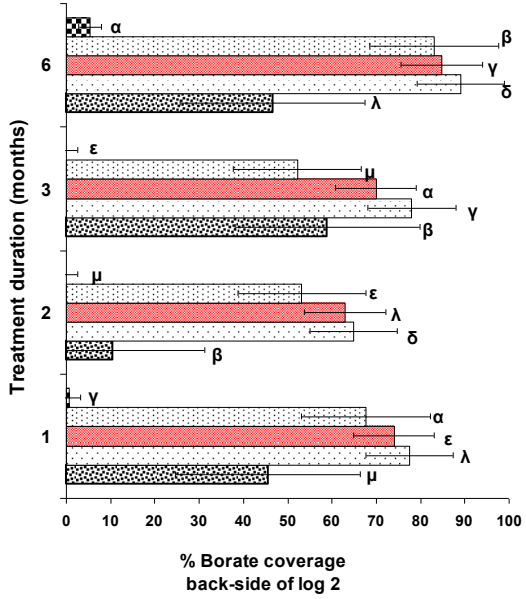
(c) Borate distribution in Black spruce log 3



(d) Borate distribution in the back-side of Black spruce log 1



(e) Borate distribution in the back-side of Black spruce log 2



(f) Borate distribution in the back-side of Black spruce log 3

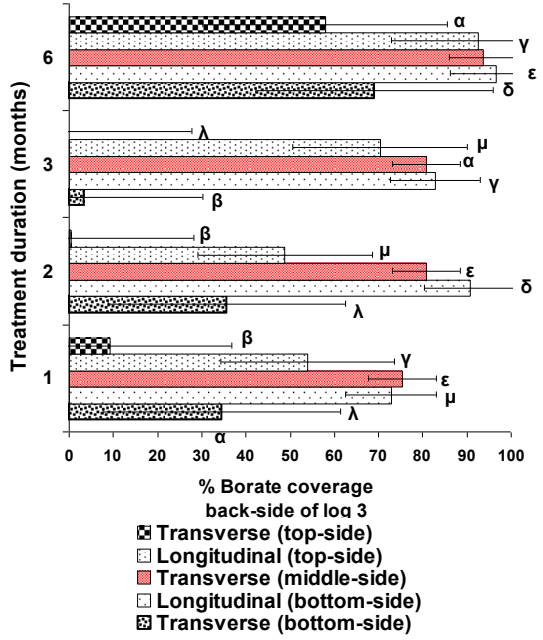
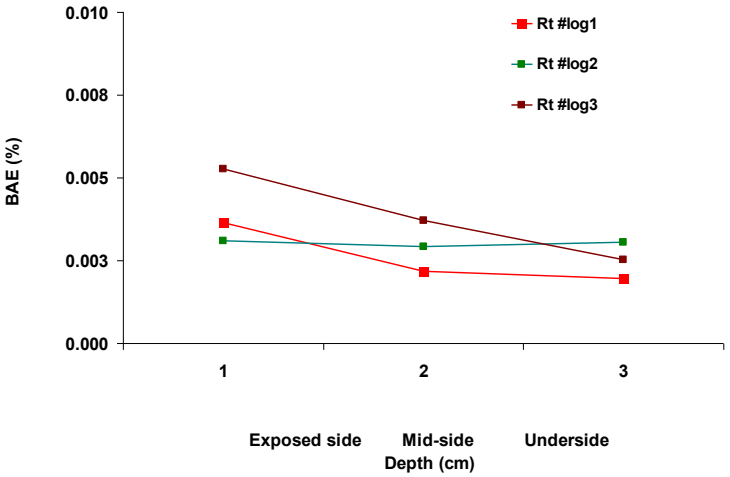
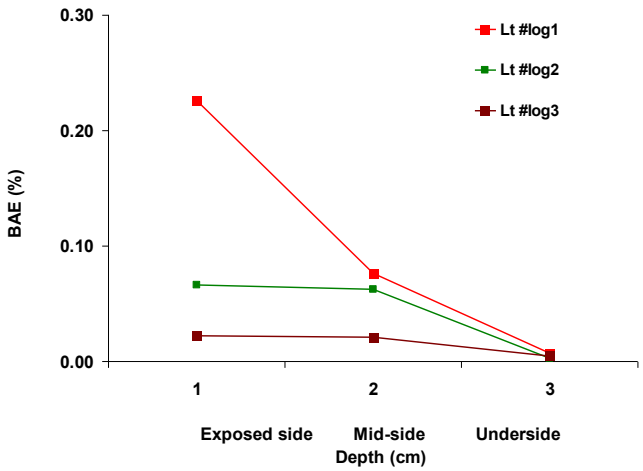


Fig.3

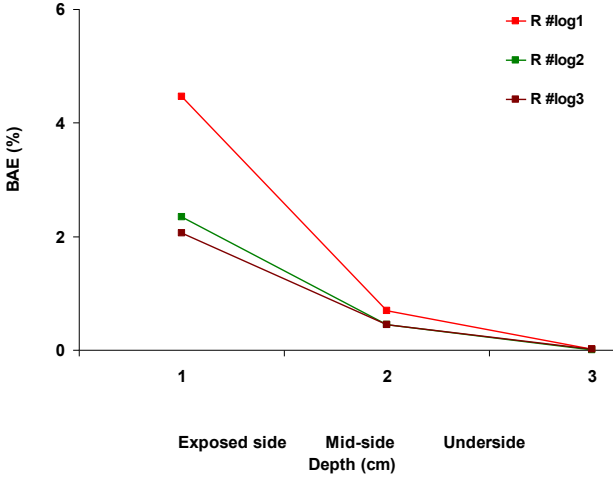
dial top-side (Rt) of Eastern black spruce, 1 month



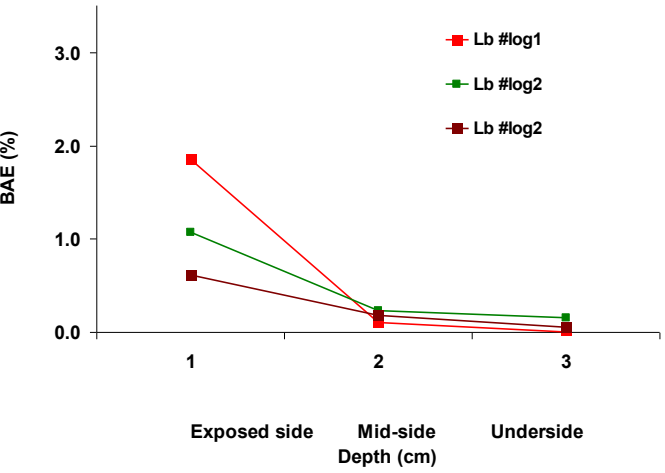
(b) Longitudinal top-side (Lt) of Eastern black spruce, 1 month



(c) Radial central-side (R) of Eastern black s



dinal bottom-side (Lb) of Eastern black spruce, 1 month



(e) Radial bottom-side (Rb) of Eastern black spruce, 1 month

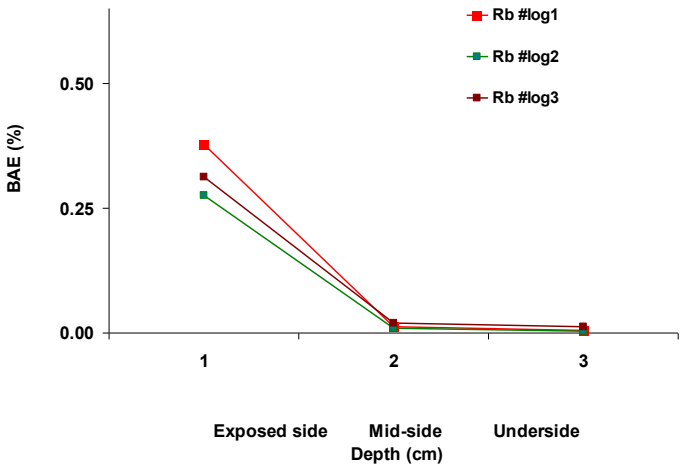
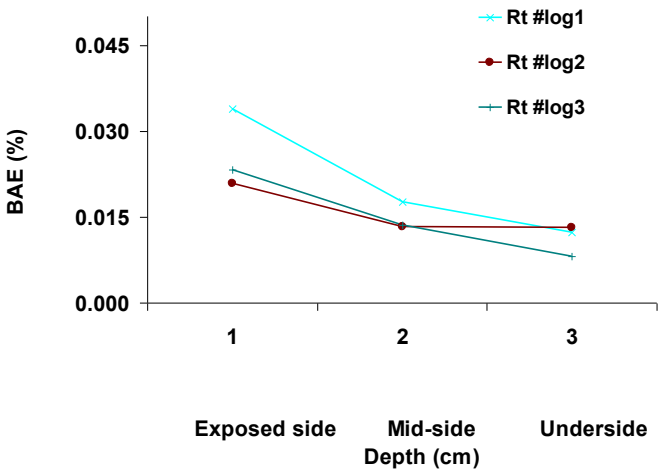
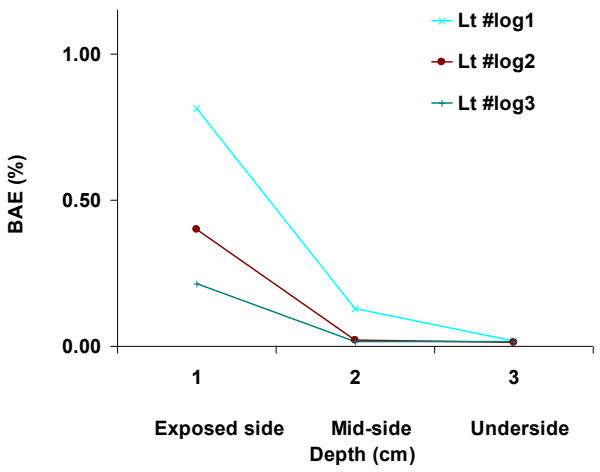


Fig.4

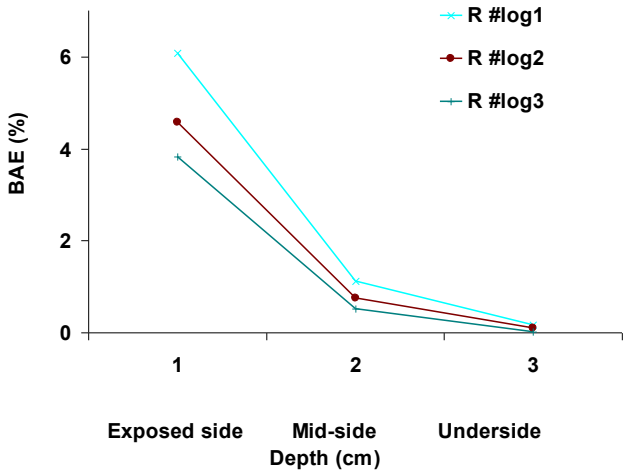
(a) Radial top-side (Rt) of Eastern black spruce, 3 months



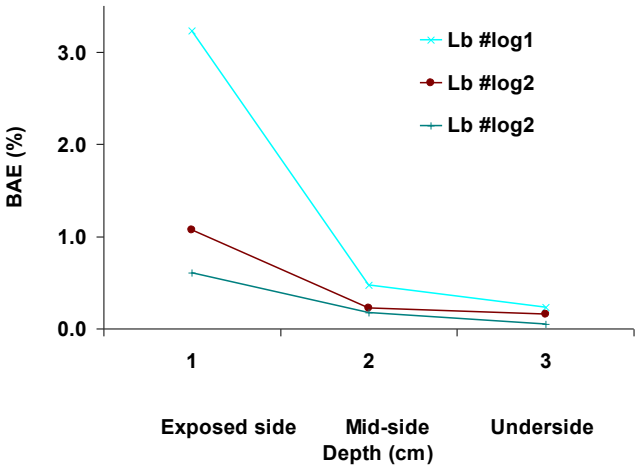
(b) Longitudinal top-side (Lt) of Eastern black spruce, 3 months



(c) Radial central-side (R) of Eastern black spruce, 3 months



(d) Longitudinal bottom-side (Lb) of Eastern black spruce, 3 months



(e) Radial bottom-side (Rb) of Eastern black spruce, 3 months

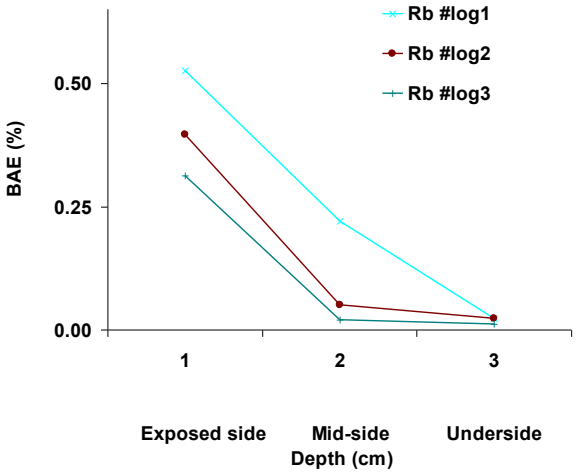
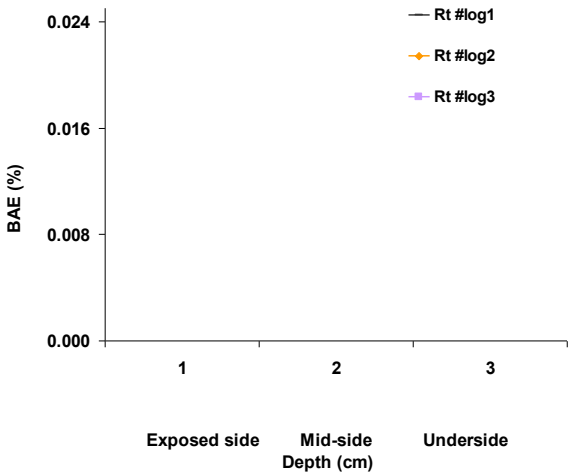
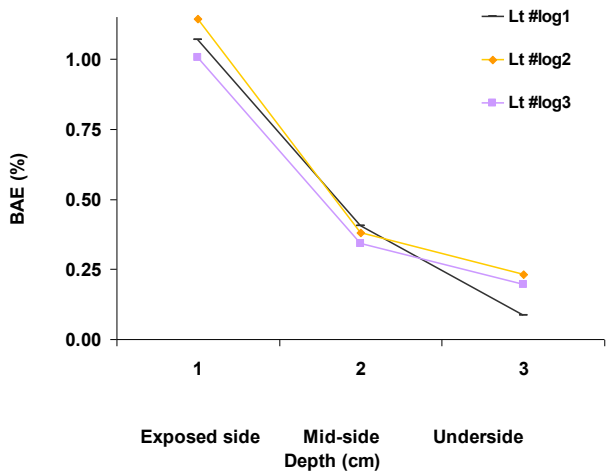


Fig.5

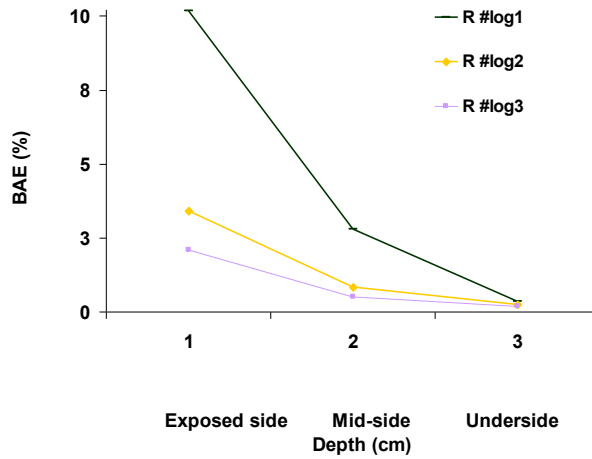
(a) Radial top-side (Rt) of Eastern black spruce, 6 months



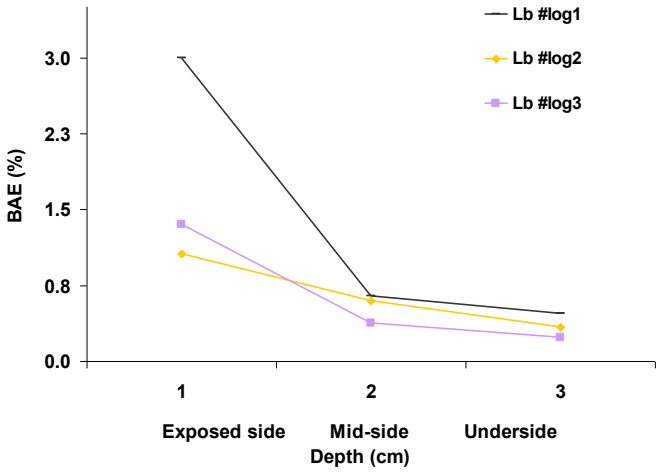
(b) Longitudinal top-side (Lt) of Eastern black spruce, 6 months



(c) Radial central-side (R) of Eastern black spruce, 6 months



(d) Longitudinal bottom-side (Lb) of Eastern black spruce, 6 months



(e) Radial bottom-side (Rb) of Eastern black spruce, 6 months

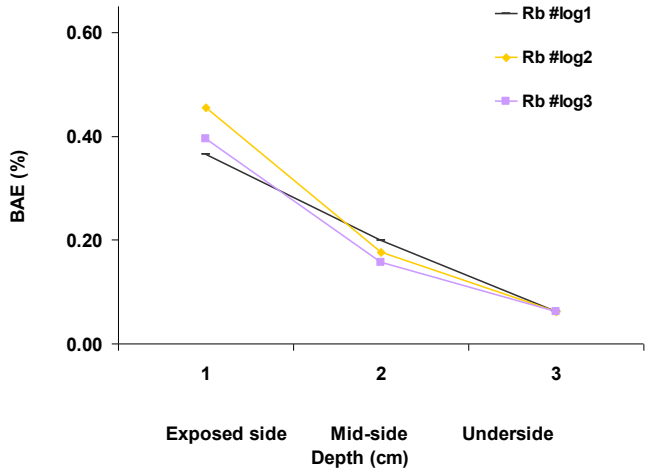


Fig.6

Evaluation of the equivalent-volume evolution of Eastern black spruce 5-layer CLT materials

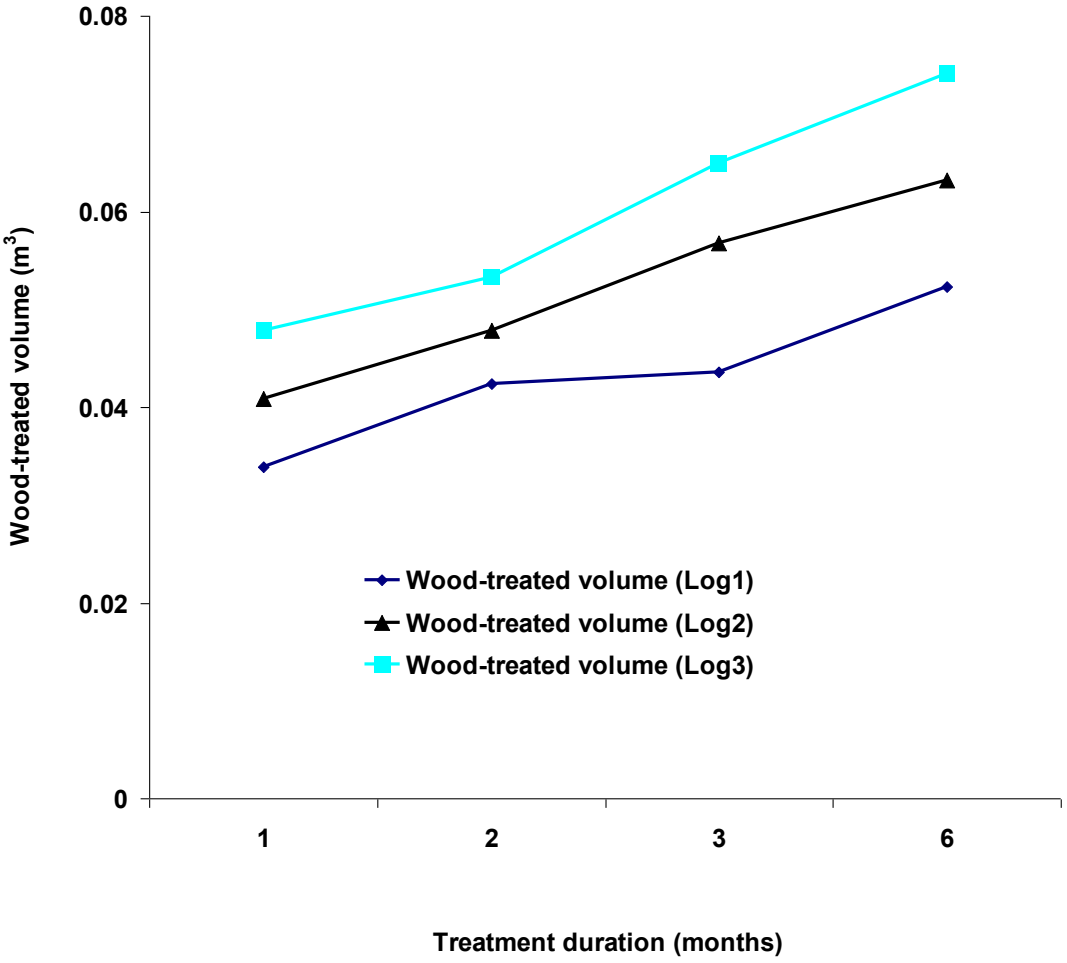
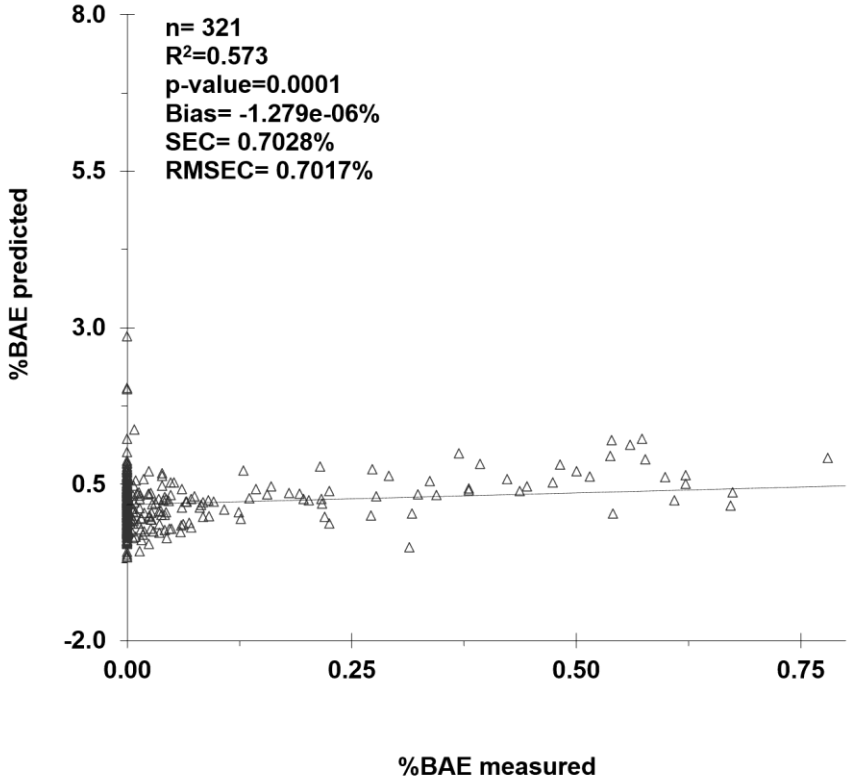


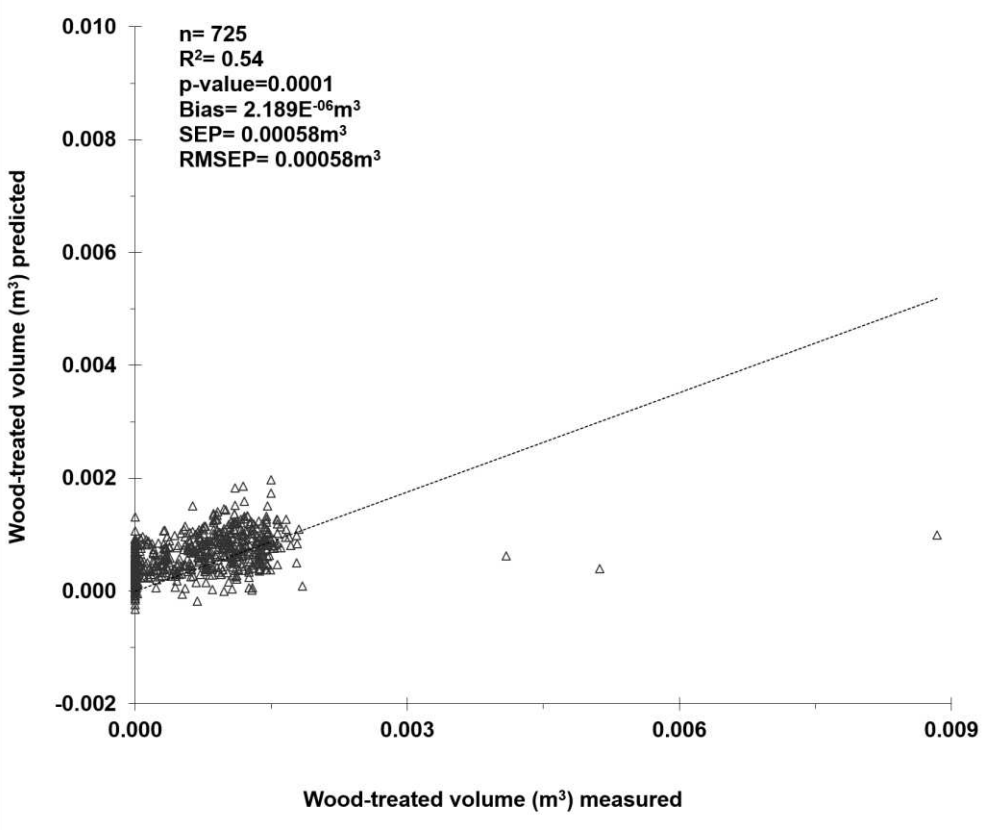
Fig.7

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(a) PLS regression based-(%) BAE diffusion in Eastern black spruce 5-layer CLT materials



(b) PLS regression-based Eastern black spruce 5-layer CLT-treated volume (m^3) with borate preservative



915 **Fig.8**

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