Determination of specific lethal heat treatment parameters for pests associated with wood products using the Humble water bath

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Abstract
Heat treatment is an effective sanitization method used for over half a century to reduce the risk of transporting pests associated with wood products. The determination of precise lethal heat treatment parameters for pests is critical for the development of globally harmonized plant protection regulatory treatment policies. Separation of heat treatment dose (time and temperature) from the factors associated with the method of heat application (delivery) and variables associated with wood characteristics allows for universal agreement on lethal dose and promotes efficient development of treatment schedule guidance. The Humble water bath is an effective and carefully calibrated heat treatment apparatus designed to test the effects of heat and determine lethal temperature doses. Specifications for building this apparatus and experimental treatment parameters are described. To demonstrate the capacities of the water bath apparatus, the effect of heat on a non-indigenous wood-boring beetle, Anisandrus dispar, is reported using heat-ramp schedules similar to industrial kiln heating applications. Adult A. dispar tested in vitro, did not survive 50 °C treatment temperature for 15 min time duration.

Keywords  Phytosanitary measures · Heat treatment parameter assessment · Forestry products · Lethal temperature · Wood borer

Key Message
- Heat treatment of forestry products is an effective and globally accessible phytosanitary treatment used to prevent pest movement into novel forest environments
- Over-treatment of wood products results in both economic and environmental costs
- Defining the lethal temperature and time period required to cause wood pest mortality independent of the heat delivery system and wood characteristic variables provides key information for development of wood heat treatment chamber schedules
- Here, we provide the specifications required to build the Humble water bath for researchers to construct and collect data for agreement on harmonized heat treatment parameters for a variety of organisms

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L. M. Humble is deceased.

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Introduction

Pest movement with forestry commodities has historically been associated with internationally traded live plants and untreated wood commodities. With the increase in trade and the use of wood packaging material to help move commodities, improved economic and environmentally responsible options for treating wood products are continuously being sought. Verification of current heat treatment guidelines and documentation of specific lethal doses for forestry pests may facilitate lower heat treatment regimes resulting in lower carbon emissions. To date a number of heat treatment experiments have documented effective lethal heat treatment parameters applied in wood tissues (in situ) using firewood and wood blocks heated with steam, dry air, electromagnetic waves, or joule heating, using current, kilns, ovens, and microwaves (Dubey et al. 2016; Hoover et al. 2010; MacQuarrie et al. 2020; Mayfield et al. 2014; Myers et al. 2009; Nzokou et al. 2008; Pawson et al. 2019; Smith 1991), and in vitro using heating blocks, vials or wooden blocks heated in water baths (Ikediala et al. 2000; Pawson et al. 2019; Smith 1991; Ramsfield et al. 2010). The lethal heat treatment studies conducted by Smith (1991) provided robust data showing that pinewood nematode Bursaphelenchus xylophilus (Steiner and Buhrer) Nickle experiences 100% mortality when subjected to 52.1 °C applied in situ and in vitro for 30 min. Sobek et al. (2011) tested the in vitro thermal tolerance of life stages of the emerald ash borer (Agrilus planipennis Fairmaire, Coleoptera: Buprestidae) including the two immature life stages most likely to be transported in association with milled wood products, 4th instar larvae, and pupae in prepupal cells. Prepubal larvae did not survive treatments of 54 °C for 15 min or longer and complete mortality was evident when pupae were exposed to 52 °C for 30 min and 54 °C for 10 min. Similarly, Mushrow et al. (2004) demonstrated that larvae, the most thermally tolerant life stages, of both Tetroplumus fuscum (Fabricius) and T. cinnamopterus (Kirkby) (Coleoptera: Cerambycidae) were killed by 30 min exposure to 50 °C or 15 min exposure to 55 °C. However, unlike the in vitro tests conducted by Sobek et al. (2011), Mushrow et al. (2004) treated Tetroplumus spp. larvae in artificially created wood chambers of varying moisture content.

In situ studies demonstrate that the method of applying heat in the infected medium is effective, however, certain factors may confound the lethal dose analysis such as variation in physical wood characteristics (e.g., moisture content, density, or temperature at the start of treatment) and application of different heating methods (e.g., convection, conduction or radiant heat transfer within the kiln). When in situ experiments are conducted in conventional heat treatment chambers such as industrial kilns, it may be difficult to ensure the temperature and duration do not exceed the required heat treatment parameters. In these studies, the measured core temperature and time often exceed the required heat treatment parameters which affects the analysis of the results. When heat treatment kiln schedules that exceed the necessary lethal dose are adopted in regulations, more stringent requirements may be imposed resulting in negative environmental impact and increased costs to industry. Acquiring data on the specific temperature and treatment duration (dose) required to devitalize wood pests independent of the factors that affect the delivery of the dose is essential to create sound, science-based regulatory policies necessary to facilitate safe trade. Separating the lethal dose of heat from the application or delivery of the heat allows for accurate determination of a specific lethal dose target.

In this study, highly precise temperature probes are used in a heated and circulating water bath capable of generating precise temperature ramps (controlled temperature increase over a specified time period), applying uniform, stable temperatures without exceeding the target temperature. When programmed to generate heating curves representative of those determined throughout the profile (including the core) of various species of wood during either heat treatment (HT) or heat treatment and kiln drying (KD-HT) regimes, this system allows for the separation of dose and factors affecting delivery. Temperature ramps to match those used in industrial kilns (heat treatment chambers) can be accommodated and tested. The Humble water bath was designed and calibrated to record highly accurate and consistent lethal dose measurements with a maximum error of 0.02 ± 0.02 °C (based on the error introduced by the datalogger and PRTs) and a target temperature fluctuations within 0.265 ± 0.063 °C. The lethal time and lethal temperature combinations are assessed using two methodologies for application of heat treatment: plunge and ramp treatments. In the plunge treatment, test organisms in glass vials are placed into a water bath, stabilized at the target temperature, and timing of the treatment duration is initiated immediately. Test organisms are withdrawn from the bath after the treatment duration is reached. The plunge test can be used to determine the minimum heat treatment required to kill pests and may be used for heat treatment regimes that apply instant heat or high heat for short durations such as those used in wood veneer sheet production or wood chip treatment. During ramp treatments, organisms in vials are placed in the water bath operating at ambient room temperature (20–22 °C) and the temperature of the bath increased at predetermined rates until the treatment temperature plateau is achieved. Timing of the treatment is then initiated and test subjects removed as the predetermined treatment durations are...
achieved. The ramp method more closely approximates operational conditions in a heat treatment chamber (e.g., drying kiln).

To test the functionality of the Humble water bath, the non-indigenous ambrosia beetle *Anisandrus dispar* (F.) (Coleoptera: Scolytinae), European shot-hole borer (Bhagwandin 1993; Wilson 1913), was chosen as a test subject due to the high prevalence of local populations. *A. dispar* is a good model test organism as the species represents a larger group of pest organisms (Scolytinae) commonly moved internationally with untreated wood products. Adult female *A. dispar* bore into the interior woody tissues (xylem) of hardwood trees, carrying with them a suite of fungi that colonize the tunnels created by beetle activity in the attacked trees (French and Roeper 1975).

The objective of the Humble hot water bath experiments is to determine with accuracy and confidence the in vitro lethal time and temperature combinations for various forest commodity pests.

**Methods**

**Water bath design and assembly**

A stainless steel water bath and immersion circulator (53 L capacity Haake S49, Thermo Fisher, Waltham, MA) was
retrofitted with a cover and specimen-treatment apparatus to control heat application and test the effects of treatment temperatures on wood pest specimens (Fig. 1). We recommend a water bath very similar to this be used to meet the design specifications described. The design and construction of the bath modifications are described in detail in the following subsections.

**Cover**

The bath unit was fitted with a 6 mm thick polycarbonate resin (Lexan) cover (527 by 425 mm) with 48 holes drilled into the cover (alternating 35 and 25 mm diameter) fitted with polyvinyl chloride (PVC) tubes (32 mm Schedule 40) secured with SciGrip 16 Low VOC Acrylic Cement (IPS Corporation, Compton, CA) to hold and guide carrier assemblies and thermocouples into the bath (Figs. 1, 2 and 3). A collar interface between the PVC tube on the cover was made from a section of PVC tube (42 mm diameter, 51 mm length) and ABS tube (48 mm diameter, 20 mm length) to adjust the height of the carrier assemblies before they are deployed in the bath (Figs. 4 and 5). Carrier assembly deployment holes (35 mm) were sealed with No. 7.5 neoprene rubber stoppers while the platinum resistance thermometer (PRT) holes (25 mm) were sealed with No. 5 neoprene rubber stoppers to reduce heat escape. To further ensure heat retention in the bath, the interface between the cover and the bath was sealed using two interior Lexan corner-edges, attached to the front and rear perimeter of the Lexan cover (425 mm apart to match the bath opening, Figs. 2 and 3) and a rubber-tube gasket, cemented to the outer edge of the bath (Fig. 1).

**Carrier assemblies**

Experimental subjects were lowered into the bath in glass vials on carrier assemblies (Fig. 4). Carrier assembly rods (carbonite 32 mm diameter and 180 mm length) were inserted into a PVC disk (8 mm thick, 32 mm diameter) and secured in place with OMEGA OMEGABOND® OB-300 High Temperature Air Set Cement (Spectris Canada, Inc; OMEGA™). On the lower side of each assembly disk, three aluminum pins were inserted into pre-drilled holes and secured in place with the cement (Fig. 4). The three equidistantly spaced metal pins differed in length from each other by 6 mm. The staggered pin length allowed heated water to flow freely around each treatment vial. 12 mm × 35 mm (0.5 dram) borosilicate glass shell vials (Fisher Scientific 03-339-30B) were attached to the carrier assembly pins using No. 000 natural latex stoppers. Stoppers were drilled from the top to a depth of 15 mm to accept 3.2 mm diameter aluminum pins. Stoppers were further secured to the vials with Petriseal™. Using this assembly, a total of 72 specimens can be tested in a single heat treatment run.

The free end of the carrier assembly rod is pushed into a hole drilled in the center of a No. 7.5 neoprene rubber stopper. This assembly allows the carrier to be adjusted to a desired depth in the bath to maximize water circulation for temperature consistency.

**Carrier assembly arrangement and deployment specifications**

Each pair of carrier assembly rows (6 rows in total) were submerged in the water at staggered depths, increasing in depth with distance from the source of heating and water circulation in the bath (Fig. 1). Initial PRT measurements taken
throughout the bath showed a minor temperature difference across the bath of $\pm 0.1$ °C with distance from the heat circulator. The staggered arrangement of carrier assembly deployment allowed for optimal water and heat circulation. Pre-measured and cut PVC tubes (160, 185 and 210 mm) were used to set the carrier assemblies to each experimental depth. Prepared vials on carrier assemblies were stored in a carrier assembly rack prior to the experiment (Fig. 1). Each shell vial stopper was labeled with a number between 1 and 84 (72 treatment vials and 12 control vials) corresponding to the position of each carrier assembly in the 4 by 6 grid of equidistantly spaced treatment locations ($n = 24$) in the bath lid. The length of the pin on which each treatment vial was attached: L[ong], M[edium] or S[hort] was included in the randomization of treatment specimens. The three peg lengths were designed to further optimize water flow and heat distribution to treatment specimens throughout the bath (Fig. 4). Experimental subjects were assigned a random position in the bath. All specimens were placed in a numbered vial before being allocated to a corresponding carrier pin according to a randomized numbering scheme.
Temperature recording

Platinum resistance thermometers (PRTs), SE 012 PT100 probe, 1/10 DIN accuracy (Pico Technology, UK) calibrated to individual channels in PT-104 Platinum Resistance data loggers (FV871/147, Pico Technology) running PicoLog6 software, Ver. 6.1.9 (Pico Technology) were used to calibrate the temperature of the water bath at each of the programmed set-points and to monitor temperatures of all treatments. Error was reduced through the individual calibration of PT 100 probes to specific channels in the PT 104 data loggers. The error and standard deviation for the three set-point temperatures (0.010, 19.317, and 39.470 °C) calibrated are −0.0054 ± 0.02 °C, 0.02 ± 0.02 °C, and 0.018 ± 0.02 °C respectively. These errors are in keeping with the Picolog PT100 calibrated with PT104 specification sheet which cites an error of 0.015 °C + 0.01% of reading (Pico Technology). For 50 °C this would be 0.015 + 0.005 = 0.02 °C.

Eight PRTs were inserted into pre-drilled (6.4 mm) holes in No. 5 neoprene rubber stoppers which were pressure fitted into 25 mm holes in the Lexan cover. Temperature data was recorded using PicoLog 6.1.6 software with readings taken across channels every 15 s (Fig. 6).

Water bath calibration

Water bath temperature calibration was required to align the bath temperature display with the actual water temperature from the PRTs to create the bath heater ramp programs. The bath was heated with a Thermo Scientific Haake PC200 immersion circulator unit, attached to the water bath using the instrument specification instructions. The difference between the circulator temperature and the temperature recorded by calibrated PRTs was measured and is used to calculate the Real Temperature Adjustment (RTA). The circulator’s RTA of 0.42 °C was calculated by taking the mean of all eight PRTs taking measurements every 15 s for 20 min. The RTA automatically adjusted programmed
set point temperatures to include the 0.42 °C offset, but the offset needed to be accounted for manually when programming ramp temperature rates.

In calibration trials, thermocouples were used to verify and measure the heat application to the test specimens. Temperatures within the treatment vials were assessed with individual thermocouple wires and resistance temperature detectors (RTD) thin film elements. Class 1/3B Pt-100 thin film platinum RTD elements, tolerance of ±0.10 + (0.0017 * T) °C (Omega Engineering Inc.) were assembled into 4-wire sensors and calibrated to individual channels on two PT-104 data loggers by Pico Technology. Individual thermocouple wires were placed in individual treatment vials at each of the 48 potential test locations in the water bath to ensure the water temperature moved across the vial (0.75–0.8 mm thickness) to the test organism, which was in contact with the vial. A number of vial configurations were tested with thermocouples to determine the best configuration and vial type. Pairing thermocouple monitoring with the platinum resistance thermometers showed that the readings from the PRTs were more stable and accurate (readings wavered by approximately ± 0.03 °C versus ± 0.005 °C respectively). Following the bath calibration, experimental heat treatments dose applications were performed and recorded using PRT readings and PicoLog 6.1.6 software.

Temperature ramp programming

Following the user manual (Thermo Scientific Laboratory Temperature Control Products Manual—Part #U01047) (Thermo Scientific 2021) ramps were programmed for each experimental treatment dose. The programmed ramps were divided into two steps in order to replicate a common heating rate of kilns in step 1 and to slow the rate of heating to minimize the temperature overshoot in step 2. In step 1, the start temperature was set at 20.42 °C (ambient room temperature + 0.42 °C offset) while the end temperature was set to 49.42 °C (0.58 °C below the target test temperature of 50 °C) to reduce overshoot of the target test temperature. At the end of step 1, the temperature ramp rate was reduced in the programmed step 2. The duration of step 1 was calculated for each treatment by subtracting the start temperature from the end temperature and dividing this number by the heating rate of 0.5 °C/min (e.g., 48 °C trial: 20.42 °C start, 47.42 °C end, 47.42—20.42 = 27, 27/0.5 = 54 min). In step 2, the start temperature was set to the previous end temperature and the new end temperature was 0.42 °C above the trial temperature to account for the adjustment between the bath sensor and the data loggers. The duration was similarly calculated by subtracting the start temperature from the end temperature then dividing by 0.2 °C/min to slow the heating cycle down to minimize the overshoot (Fig. 6) above the trial temperature (e.g., 48 °C trial: 47.42 °C start, 48.42 °C end, 48.42—47.42 = 1, 1/0.2 = 5 min duration).

Collection of test subjects

Host material was collected from a variety of Prunus avium (L.) (sweet cherry) cultivars, from trees growing at the Canadian Food Inspection Agency’s Centre for Plant Health (Saanich, BC) known to be infested with A. dispar in September 2020. Cut ends were sealed with paraffin wax to maintain moisture in the stem section until dissected for experimentation. Adult A. dispar beetles were carefully dissected from the wood and stored in a temperature-controlled cabinet at 20–23 °C in petri dishes with moistened filter paper, assessed for vigor, and identified to species and sex.

Application of treatments

A series of heat treatment experiments were conducted; in each successive experiment the treatment temperature was decreased by 2–4 °C as results showed lethal effects on the test subjects. Treatment temperatures 54, 50 and 48 °C were applied with a heating ramp rate of 0.5 °C/min, reduced for the last 5 min to 0.2 °C/min and held at temperature for three treatment time durations (Fig. 7). The ramp rate of 0.5 °C/min is based on the kiln rate in MacQuarrie et al. 2020, which used an experimental kiln to test the effects of heat on the wood borer Agrilus planipennis in ash (Fraxinus). The heating rate for sawn wood treated in industrial kilns varies depending on a variety of parameters including:

![Fig. 7 Percent survival of 72 A. dispar adults (per treatment temperature) after exposure to 48, 50 and 54 °C for 0, 15 and 30 min treatment durations. Individuals treated to 54 °C and removed upon reaching the target temperature (0 min treatment time), exposed to the 54 °C treatment temperature for 15 and 30 min did not survive. Individuals treated to 50 °C for 15 and 30 min did not survive. Individuals treated to 48 °C showed decreased survivorship when treated for 30 min. Individuals in control groups showed between 80 and 100% survival](https://link.springer.com/article/10.1007/s10989-022-02737-7)
Subjects were heated to the experimental target temperature and held for one of three treatment time durations: 0, 15, or 30 min plus a control where specimens did not experience heating above ambient temperature. The bath was initially filled with half room temperature and half cooled (3 °C) Milli-Q water (Milli-Q Integral 10 unit, MilliporeSigma Burlington, MA) and heated to the standardized start temperature of 20 °C before specimens were lowered into the bath to control for start temperature across experiments. For each treatment duration, the subjects experienced a controlled increase of temperature (ramp) in the bath from the start temperature. For example, for the first treatment duration (0 min) the test subjects were lowered into the bath at 20 °C (recorded as 20.42 °C on the bath circulator), followed by an increase of temperature to the target temperature, and immediate removal from the bath. Individuals experienced increasing temperatures over 59, 63, and 71 min heating durations for the experimental target temperature treatments of 54, 50, and 48 °C respectively. For the 15 and 30 min durations, individuals were removed 15 and 30 min after the target temperature was reached. The return of subject temperature to room temperature after removal from the water bath occurred within 2–3 min. The actual treatment duration includes the exposure to increasing temperatures to the target temperature, time at the target temperature, and a short cooling phase from the target temperature until removal from the vials. Twenty-four A. dispar were assigned to each timed treatment category with twelve controls per temperature treatment.

In a final experiment, plunge dose effects were tested by exposing individuals to a treatment regime without exposing specimens to the ramp program bath temperatures. The water bath heater was set to the treatment temperature and upon reaching the target temperature, individuals were plunged into the bath for the designated treatment time. Post-treatment cooling to room temperature occurred naturally over a short duration of time. Treatment temperatures 50 and 48 °C for 30 min were tested on 72 A. dispar specimens.

**Post-treatment assessment**

Test subjects were removed from treatment vials, placed in individual sterilized petri dishes with moistened filter papers and held at 20–23 °C in a temperature-controlled cabinet. Samples were assessed daily on a mobility scale from 0 (active or normal movement), 1 (limited or compromised movement), and 2 (no movement). Treatment effects were noted and included liquid droplets on the body of the beetles—suggesting cuticle rupture, and damaged body parts for example, neck oriented in an extended position, unattached tarsi etc.

**Results and discussion**

The Humble water bath treatment apparatus is unique in its calibrated, uniform application of heat, operating without confounding variation in wood characteristics, and with careful control of targeted heat treatment parameters. Separating the dose (temperature and time) of heat treatment from the delivery or from the factors that affect the delivery, helps identify effective lethal temperatures with or without exposure to ramp up and cool down temperatures. The benchtop Humble water bath is portable, efficient and economical to procure and assemble.

Previous heat treatment studies have employed a variety of heat delivery methods (e.g., joule heating, dielectric heating, microwave heating, vacuum steam heating and conventional heat treatment), both in vitro and in situ on a number of agricultural and forestry pests. These studies have been used to form the basis of phytosanitary regulations to ensure the safe trade of agricultural and wood products. The Humble water bath described herein provides a standardized, highly calibrated method to test a wide variety of organisms, with the ability to separate the lethal dose of heat from variables affecting the application or delivery of the heat. Previously, dose and delivery were inseparably measured and lack of in situ experiments with high specimen numbers may have resulted in higher heat treatment parameters required in regulatory policy. Historic regulatory heat treatment requirements for some wood commodities may have been unnecessarily high because the determination of target temperatures was confounded by the physical effects of wood characteristics. We propose that the current approach of lethal temperature determination that incorporates delivery and more accurate dose considerations will allow for the development of effective, economic and environmentally sound temperature treatment parameters and subsequent regulations.

We demonstrated the effectiveness of the water bath using Anisandrus dispar as a test organism. One hundred percent mortality of adult A. dispar was achieved at 50 °C for 15 min and 54 °C for 0 min. These results were obtained using the ramp-up method in which the water bath and beetles were gradually warmed from 20 °C to the target temperatures over a period of 63 (50 °C) or 71 (54 °C) min. Lower temperature exposure results provide evidence of sub-lethal effects. Heat treatment of A. dispar at 50 °C for 15 and 30 min and 54 °C
for 0, 15, and 30 min was determined to be lethal to all test subjects (Fig. 7). Individuals in the 54 °C treatment were non-mobile after heat treatment and designated dead after 24 h. Individuals exposed to 50 °C for 30 and 15 min were designated dead after 24 h; two thirds of the 0-min treatment group were healthy while one third were compromised (sub-lethal effects observed). In a final experiment testing dose effects by plunging vials into the target temperature, all individuals treated to both 48 and 50 °C for a 30 min duration did not survive.

The current results align with ISPM 15 required heat treatment parameter specifications for application of 56 °C for 30 min (throughout the profile of the wood) (IPPC 2021). The results of the current study are in keeping with lethal heat treatment parameters demonstrated in previous studies for bark and ambrosia beetle species: Xyleborus affinis (Merkel and Tusnadi 1992), Xylosandrus germanus treated in vitro, rapidly heated (rate between 1.3 and 1.7 °C/ min) in a hot water bath died at 46 °C for 30 min (Merkel and Tusnadi 1992), and Pityophthorus juglandis Blackman tested in situ and placed in heated water, died at 46 °C for 30 min (Suh 2014), and Pityophthorus juglandis Blackman tested in situ with steam heat treatment did not survive exposure to 52 °C for 30–40 min (Mayfield et al. 2014). Using A. dispar as a test subject we have demonstrated that a lethal temperature can be accurately determined under highly controlled conditions using the Humble water bath. For the purposes of demonstrating the functionality and precision of the Humble water bath the A. dispar trial was not replicated for each temperature time and duration. Full independent replication for lethal dose testing with statistical confidence for future experiments is recommended for phytosanitary treatment applications (as guided by ISPM 28 or in dialog between trading partners; IPPC 2021).

While the Humble water bath provides precision in identifying the lethal temperature for a test organism, determining the duration of heat treatment exposure accurately is more challenging. Two approaches for applying heat to the test organisms were explored. First, the plunge method, where vials were immersed into the water bath at treatment temperature, held for a specified time and removed, allowed for control over the duration of exposure. Second, the ramp method can be used as a proxy for the conditions experienced by organisms heat treated in situ in wood treated in a commercial heat chamber. Vials gradually heated from room temperature to treatment temperature, held for the specified time and removed exposed the test organisms to a range of temperatures as the bath approached treatment temperature. For example, individuals treated to 56 °C for 30 min experienced temperatures between 22 and 56 °C for 41 min (71 min total treatment time). In both cases, the test organisms experienced rapidly decreasing temperatures following removal from the bath as they cooled to room temperature. In situ, the ramp down is slower due to the insulating effects of the wood fiber (density, moisture, dimensions etc.). The time to ramp down exposes pests to prolonged sub-lethal temperatures and could be considered a component of the heat treatment or overtreatment. The importance of these pre- and post-treatment exposures is not clear. Treatment at the lower target temperatures did not result in mortality but there was some indication of sub-lethal effects. The gradual exposure to increasing temperatures experienced in the ramp process could induce thermal conditioning affecting the kinetics of thermal death (Lester and Greenwood 1997). The physiological effects of gradual heat treatment, both sub-lethal and lethal need to be further characterized. This is especially true given the gradual heating and cooling processes used in commercial practice and the possibility that organisms in wood might adapt to thermal exposure. To further explore and understand the importance of exposure to sub-lethal temperatures that occur in situ, the water bath could be used to isolate the ramp up, treatment and ramp down components. The Humble water bath provides the necessary precision to pursuit such questions.

To continue to develop globally harmonized heat treatment parameter guidelines, accurate determination of lethal temperatures across a wide range of pest taxa is needed. Understanding sub-lethal effects at lower temperatures and the possible effects of thermal conditioning to pest survival are critical in the development of heat treatment schedules. Additionally, understanding the effects of temperature change (ramp up and down from treatment temperature will assist in coordinating phytosanitary treatment requirements with commercial kiln schedules. Finally, understanding wood characteristics and how they contribute to treatment and overtreatment due to the heat dynamics (conduction, convection and radiation) within the tissues and surrounding space will help to combine lethal treatment data to develop efficient commercial heat chamber schedules that are effective at meeting phytosanitary requirements.

Providing lethal heat treatment data for specific pests or life stages of pests suspected of having extreme heat tolerance will help us understand thermal physiological responses in pest organisms and provide confidence in globally accepted parameters and guidelines for all pests. Performing such work on quarantine pests is challenging and potentially dangerous to conduct outside of the natural range of the pest organisms. We envision a global collaborative testing initiative using common experimental protocols based on the Humble water bath. We recommend researchers around the world construct the Humble water bath to test organisms (insects, nematodes, fungi etc.) of phytosanitary significance in their territory and determine their accurate lethal heat dose in order to gain confidence and consensus on the heat treatment parameters required to ensure heat treated wood commodities can be traded safely while minimizing environmental impact.
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Author contribution All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Leland Humble, Meghan Noseworthy, Tyranna Souque, Josie Roberts and Esme John. Leland Humble conceived and designed the research. Leland Humble, Meghan Noseworthy, Tyranna Souque, Esme John and Charlene Lloyd conducted experiments. Tyranna Souque and Esme John prepared figures. The first draft of the manuscript was written by Meghan Noseworthy and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The data sets generated during this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Conflict of interest The authors have no relevant financial or non-financial interests to disclose. I declare that the authors have no competing interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

Consent to publish Not applicable.

Consent to participate Not applicable.

Ethical approval All applicable national and provincial guidelines for the care and use of animals were followed.

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