Efficacy of commercial microwave equipment for eradication of pine wood nematodes and cerambycid larvae infesting red pine

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Abstract

The feasibility of using commercial 2.45-GHz microwave equipment to kill cerambycid larvae and pine wood nematodes (PWN) [*Bursaphelenchus xylophilus* (Steiner and Buhrer) Nickle] infesting lumber was investigated. Research goals were to test a system of separating green material into moisture content (MC) ranges and to determine the feasibility of using internal wood temperature as the critical lethal treatment parameter. Prior research suggested that MC is a critical factor to consider in scaling up from laboratory-scale experiments with small volume specimens to full-sized lumber using commercial treatment processes. Commercial units used for this study were a chamber design unit for batch irradiation treatment and a continuous conveying tunnel design of microwave equipment fitted with optional air heaters. Because red pine is a preferred host of PWN and has high wood MC, microwave irradiation trials were conducted with red pine directly obtained from freshly sawn logs. The trials conducted using batch irradiation resulted in 100-percent mortality in all treated red pine materials (4- by 4- by 20-in cant samples) infested with PWN or beetle larvae above a measured wood temperature of 62°C, regardless of wood MC. In contrast, treatment of 1-inch-thick boards using continuous feed microwave irradiation achieved 100-percent morality at lower wood temperatures. These results were encouraging and indicate commercial microwave (2.45 GHz) treatment may be a feasible alternative to conventional heat treatment or methyl bromide fumigation.

Commercialization of microwave processes to eradicate exotic pests infesting lumber may provide a useful tool for nations endeavoring to exclude these invasive pests from inadvertently crossing their borders in wood pallets and crates or other forms of solid wood packing material. Introduction of pine wood nematodes (PWN) [*Bursaphelenchus xylophilus* (Steiner and Buhrer) Nickle] and cerambycids, such as the Asian longhorned beetle *Anoplophora glabripennis* (Motsch.) (Coleoptera: Cerambycidae) (ALB) into new habitats threaten forest resources around the world (USDA APHIS 1998, Nowak et al. 2001, Krehan 2002, Mota et al. 1999). PWN causes a serious wilt disease in several pine species and is vectored by cerambycids (Wingfield et al. 1982). Currently, kiln treatment and methyl bromide fumigation are the only two sanitization treatments internationally approved for solid wood packing materials under the auspices of the United Nations (U.N.) (UN FAO 2002). However, the U.N. phytosanitary commission is also seeking alternative technologies, such as microwave energy, which can be used for this application. The goals of this study were to test a system for separating wood for treatment (1- by 4-

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by 20-in and 4- by 4- by 20-in red pine) into moisture ranges by green weight and to determine the feasibility of killing nematodes and cerambycids in commercial equipment using temperature as the critical treatment parameter.

Microwave energy is used commercially for a number of applications such as foundry core drying, ceramic filter drying, rubber vulcanization, chemical vapor deposition, mold drying, and chemical waste processing (Cober 2004). In the wood products industry, TrusJoist – A Weyerhaeuser Business (Strand 2002) consolidates veneer cut strands into processed composite lumber applying microwave energy. In addition, scientists are evaluating the use of microwave irradiation for control of termites, powder post beetles, and woodworm larvae in wood, as well as ALB larvae in living trees (Burdette et al. 1975, Jiang et al. 1991, Andreuccetti et al. 1994, Lewis et al. 2000). Microwave irradiation (2.45 GHz) is also lethal to cerambycid larvae such as the ALB and the cottonwood borer beetle (CWB), *Plectrodera scalator* (Fabricius) (Coleoptera: Cerambycidae), in laboratory-sized wood samples (Fleming et al. 2003, 2004). Also, as moisture content (MC) of wood increases, additional microwave energy is required to ensure mortality of insect larvae in wood (Fleming et al. 2003).

Methods and materials

Equipment

Both continuous and batch 2.45-GHz microwave systems (Cober Electronics, Inc., Norwalk, CT) were used in this study. The continuous system was designed for industrial applications. The microwave chamber was 10- by 10.5- by 72-inches long with an oven opening 8 inches wide by 2 inches high. A Teflon fiberglass conveyor belt (5 in wide) was positioned approximately 5 inches from the bottom of the chamber. Conveyor speed was variable for 0 to 100 feet per minute (fpm). Forced air, either room temperature or heated with an 18-kW electric resistance heater (maximum temperature 260°C, 500°F), flowed through the chamber at 1,000 fpm. Forced air temperature was measured with a thermocouple (type J). One 2-kW generator was connected to each of six portals (two located on the bottom of the chamber near the entry and exit openings and two staggered on each side of the chamber). This provided a combined maximum of 12 kW of microwave power, although a maximum of 7 kW of input power was used for these experiments at the request of the equipment owner; a second limitation was use of the continuous system for one day.

The batch system used in this study was designed for testing purposes, not for industrial use. The chamber dimensions were 28 by 28 by 20 inches high. A fan provided some airflow (non-measurable) through the chamber. One generator (6 kW, 2.45 GHz) supplied microwave power to the system. A circular turntable, approximately 20 inches in diameter, was positioned 1 inch from the bottom of the cavity allowing load rotation if desired. Since the microwave field is at zero at the walls of the chamber and at the metal turntable, a 1-inch-thick polymer disk 20 inches in diameter was placed on top of the turntable so the entire wood load could be irradiated. Without this polymer layer, the wood surface touching the metal turntable, as well as nearby bulk material, would experience a near-zero microwave field, as evidenced by a minimal increase in wood temperature (Fleming, unpublished data). Three fiber optic probes with a temperature monitoring range between –40° and 400°C (Ipitech, Carlsbad, CA part no. 13-4600-0001) were threaded through a port in the sidewall of the batch system chamber. The phosphor tip and fiber optic cable are sheathed in a fluoropolymer with a total length of approximately 6 feet. Each probe was connected to a single channel, signal processing unit (LumiTherm® 500, Ipitech, Carlsbad CA). The LumiTherm 500 system uses a pulsed light source, which travels down the fiber optic cable and energizes the phosphor. Since temperature affects the time-decay of the phosphor glow, the sensor records the phosphor intensity and the signal processing system converts it to a temperature reading.

Insects and nematodes

The CWB larvae used in this study were reared by the USDA Forest Service facility in East Lansing, Michigan, on a meridic insect diet (Payne et al. 1975, Fleming et al. 2003). Individual larvae were maintained in diet cups at room temperature until needed for experiments. At the time of irradiation, larval weight ranged from 0.80 to 2.25 g. One larva was placed inside a pre-drilled hole in the wood sample (as described below), and a wood plug was used to cap the hole. Once the sample was irradiated, the larva was removed and its status (living or dead) was determined by visual observation of:

1. movement or the lack of it,
2. discoloration, and/or
3. dehydration as described in Fleming et al. (2003).

Control larvae were similarly placed in a drilled hole and removed, but not irradiated.

Pine wood nematodes were reared at the Penn State University, Fruit Research Center facilities in Biglerville, Pennsylvania. Nematodes were reared on a pure culture of the nonsporulating fungus, *Botrytis cinerea* (Pers.). The fungus was cultured on sterile, damp white prose millet seed (Guerney's Seed and Nursery Company, Greendale, IN) as described by Myers (1988).

The number of living nematodes inserted into a wood sample in a volume of 250 µl of water was estimated by taking the mean of the live nematodes counted in three separate samples. An alternate method used was to take the mean of three counts of each of two separate dishes. The 250-µl nematode solution was inserted into 0.25-inch diameter hole (0.625 in deep) drilled into the bottom of a large plug (0.75-in diameter), and a small plug (0.25-in diameter) was placed in the hole to contain the nematodes (**Fig. 1**). The entire plug assembly was inserted into a 4- by 4- by 20-inch wood sample, nematode-side down, before irradiation. This configuration placed the nematodes near the center of the sample cross section. After irradiation, the entire plug assembly was removed from the wood samples and shipped with the control plugs (no microwave treatment) overnight to Biglerville, Pennsylvania, for nematode recovery. All nematodes were recovered within 48 hours. In preliminary experiments, it was found that shipment did not affect nematode recovery.

After weighing each red pine sample, the small plug was removed from the large plug. The large plug was split in half with a small knife, splitting the hole lengthwise. A squirt bottle filled with tap water was used to flush both sides of the hole. The water was captured in a beaker, and the nematodes were allowed to settle before splitting the sample into two counting dishes. Nematodes were counted using the stereo dissecting microscope and status was recorded. Due to the number of samples irradiated per day, it was not possible to count all of the

nematodes in every sample. Therefore, if a live nematode was observed in a given sample, the treatment was deemed ineffective and counting of that sample ceased. For a small number of the samples, both the dead and live nematodes were counted. The plugs were then dried in a 40°C incubator for a minimum of 48 hours and weighed to determine moisture content (MC) before treatment and after shipping.

Sample preparation

Freshly felled logs of red pine (*Pinus resinosa* Ait.) were bucked into 8- to 10-foot lengths for ease of handling and transport. The harvested logs were sawn to obtain samples measuring 4- by 4- by 20-inch cants or 1- by 4- by 20-inch boards. An effort was made to control sample preparation to minimize knots that might affect the desired placement of CWB larvae or nematodes. Holes for the insertion of either nematodes or cerambycid larvae were carefully drilled in the wood samples. For the 4- by 4- by 20-inch samples, holes were centered across the face at 2, 5, 6, or 10 inches from the end of the cant. Holes for nematodes were prepared as described above (**Fig. 1**). The fiber optic probe holes were drilled with a #49 diameter drill bit (0.073 in) 1-7/8 inches deep within about 1/8 inch of the larva/nematode hole.

For the 1- by 4- by 20-inch samples, one hole (2-1/8-in deep, 17/32-in in diameter) was drilled 10 inches from the end into the edge of the board. A second hole, 1/8 inch from and perpendicular to the larva/nematode hole, was drilled for the thermocouple probe (Omega, Model 881C digital multimeter).

Batch microwave system experimental design

Previous experiments on laboratory-sized samples showed that wood MC affects the microwave dose required to obtain 100-percent mortality (Fleming et al. 2003). To minimize the microwave energy required to ensure that the nematodes/larvae were dead, loads should consist of wood with similar MC. Since MC calculations for each wood sample are based on ovendry weight (ASTM 1996), actual wood MC could not be determined for a green sample until after the experiment was completed and the sample was ovendried. To irradiate samples of similar MC together, the MC was estimated for each sample using Equation [**1**].

$$SW_{green} = SG(MC + 1)V_g \qquad [1]$$

where:

SW = weight of green sample (g),
SG = specific gravity (g/cm^3),
MC = fractional moisture content of sample, and
V_g = green volume of sample (cm^3).

The approximate specific gravity (SG) was estimated by averaging the SG calculated for 36, red pine samples (4-in cubes) using ASTM standard D 2395 Method A (ASTM 1996). A green SG value of 0.36 was determined for the cant material often obtained from the inner saw log portion. Since most of the study materials cut from log cores contained substantial proportions of juvenile wood, this value was used instead of the published SG for red pine, 0.41, which is for small, clear, straight-grained wood (USDA 1999). The SG estimation described above was used, along with the approximate volume for 4- by 4- by 20-inch wood sample material, to construct a spreadsheet for expected green weights corresponding to 5 percent MC intervals. After initial processing, each wood sample was weighed (nearest gram weight basis) and placed in one of the following four groupings according to MC:

- very high (VH),
- high (H),
- medium (M), and
- low (L) (**Table 1**).

Three configurations of 4- by 4- by 20-inch cant sections were irradiated to determine volume and shadowing affects and to help establish appropriate power level settings for the batch microwave chamber. **Figure 2** shows the configurations, and **Figure 3** illustrates graphically the time vs. temperature profiles. Configuration a) has three rows by four columns with 0.75-inch stickers below each row. Larvae were inserted into holes positioned as follows relative to the end toward the front of the chamber: A1 and C3 at 2 inches, B2 at 6 inches, A3 and B3 at 10 inches, and C4 at 15 inches. Fiberoptic probes were inserted into the smaller (0.073 in) holes drilled near the larger hole with larvae in A1, B3, and C4. Configuration b) with two rows by four columns had larvae in A1 at 2 inches, B3 at 6 inches, A2 at 10 inches, and B4 at 15 inches, and nematodes in

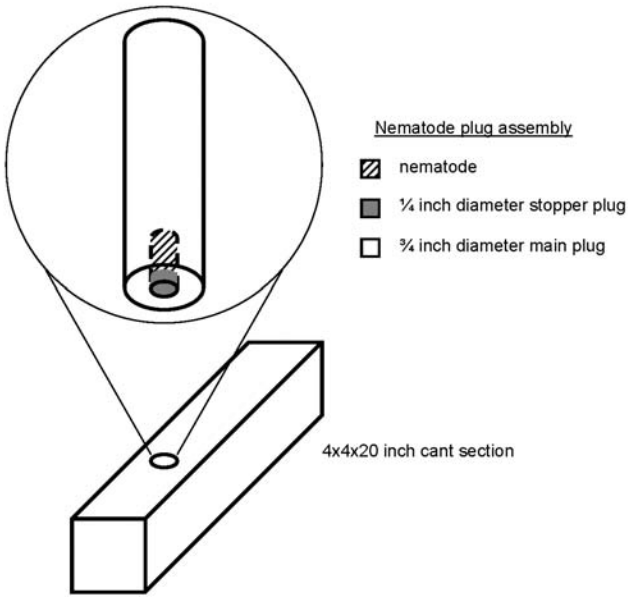

Figure 1. — Illustration of plug assembly used to place nematode solution toward the center of the red pine 4- by 4-inch cross section before microwave irradiation.

Table 1. — Targeted MC and predicted green weight of red pine samples with 4- by 4- by 20-inch dimensions for each of four MC groupings.

MC grouping	Targeted MC range	Predicted green weight range (g)	
		0.36 SG	0.41 SG
	(%)		
Very high	VH > 150	VH > 4720	VH > 5375
High	110 < H < 145	3964 < H < 4625	4515 < H < 5267
Medium	65 < M <105	3114 < M < 3870	3547 < M < 4407
Low	L < 60	L < 3020	L < 3440

B1 at 5 inches, A3 at 10 inches, B2 at 14 inches, and A4 at 18 inches. Probes were placed in A2, B1, and B4. Configuration c) has a single row of four across with nematodes placed in A1 at 6 inches, A2 at 15 inches, A3 at 2 inches, and A4 at 10 inches with probes in A1, A3, and A4. The turntable was not operational for batch experiments to avoid damage to the fiberoptics.

Input power of 1,000 W (1 kW) was first used to irradiate Configuration a) which proved inadequate as can be seen in **Figure 3** from the extended time period needed to reach desired temperatures. Additionally, the large volume accompanied by the apparent shadowing affect, recognizable from the large temperature differences, made it necessary to increase power to 3 kW. Ultimately, configuration c) was chosen for the rest of the experiments ($n = 45$) in the batch microwave system.

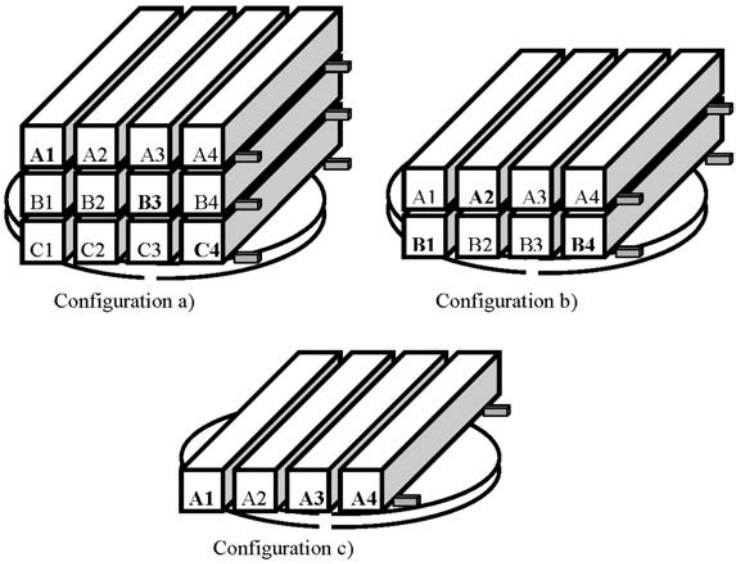

Figure 2. — Cant section configurations used in the batch microwave chamber with larvae and/or nematodes distributed throughout the charge and temperatures monitored near the organisms in the sections marked in bold.

Four to six loads for each MC grouping (VH, H, M, and L) of red pine infested with larvae were irradiated at 5,000 W until all fiber optic probes registered at least 62°C. After this critical temperature was reached, the plug was removed from each sample. Each larva was then removed from the wood sample and its status (live/dead) was determined. For treating nematodes, the samples (five loads of VH, M, and L MC groupings, 10 loads of H MC) were also irradiated at 5,000 W until probes registered at least 62°C. Once removed from the sample, the nematode plug assemblies were shipped to Biglerville, Pennsylvania, overnight in an insulated freezer bag with ice packs. Recovery and counting of live nematodes was completed within 72 hours of microwave treatment. Controls consisted of larvae or nematodes handled in the same manner, but the microwave was not turned on.

Continuous microwave system experimental design

Red pine samples containing a mixture of sapwood and heartwood (1- by 4- by 20-in long) were separated by green weight into three groups with average weights of 979 g (867 to 1103 g), 1201 g (1115 to 1319 g), and 1402 g (1207 to 1680 g), referred to as medium, high, and very high green weight, respectively. One trial ($n = 10$) evaluated the efficacy of microwaves for killing pine wood nematodes using wood from each weight grouping, while the other trials tested efficacy against cerambycid larvae. Boards were placed on the moving conveyor belt end-to-end to obtain a consistent load inside the chamber at any moment in time. The high ($n = 30$) and very high ($n = 20$) weight samples were irradiated at 7 kW, while the medium weight samples ($n = 60$) were irradiated at 6 or 5 kW. Because the belt was moving at 2.6 ft/minute, total time in the 6-foot chamber for a single sample was 2.31 minutes. Due to system design, forced air always circulated through the chamber at 1,000 fpm while the equipment was in operation. It was observed in test runs with non-infested wood of high and very high green weight that the wood temperature was not consistently reaching 63°C at the maximum input power of 7 kW, even at the slowest conveyor belt speed. With chamber heat added, however, interior wood temperature in the test samples was generally higher. Therefore, some samples were run with chamber air temperature at 33°C (91°F) and others at 110°C (230°F). After the sample came off the belt, a thermocouple was immediately placed inside the predrilled hole and a fiber optic probe was placed on the surface to register the internal and surface temperatures. The larvae or nematodes were then removed from the sample and their status (living/dead) was determined in the same manner as the batch experiments described above.

Table 2. — MC calculations for each grouping assuming 0.36 SG of 4- by 4- by 20-inch samples

MC range	Mean ± SD actual MC	Maximum actual MC	Minimum actual MC	COV
		(%)		
Very high	120 ± 23	178	86	19.1
High	84 ± 9	118	71	10.7
Medium	67 ± 11	84	43	16.4
Low	36 ± 6	47	25	16.6

SD = standard deviation; COV = coefficient of variation.

Results and discussion

Batch microwave experiments

The average, maximum, and minimum MC for each wood grouping (VH, H, M, and L) are shown in **Table 2**. Comparison of the actual sample MC to the predicted wood MC using green weight using either the SG value of 0.36 obtained through sampling or the published SG value of 0.41 in Equation [**1**] did not produce accurate results (paired t-test: $t = -14.0$, $df = 124$, $p < 0.0001$; $t = 2.24$, $df = 169$, $p = 0.0262$, respectively). There was, however, a strong, linear relationship between MC as predicted by Equation [**1**] and actual MC for both SG values of 0.41 and

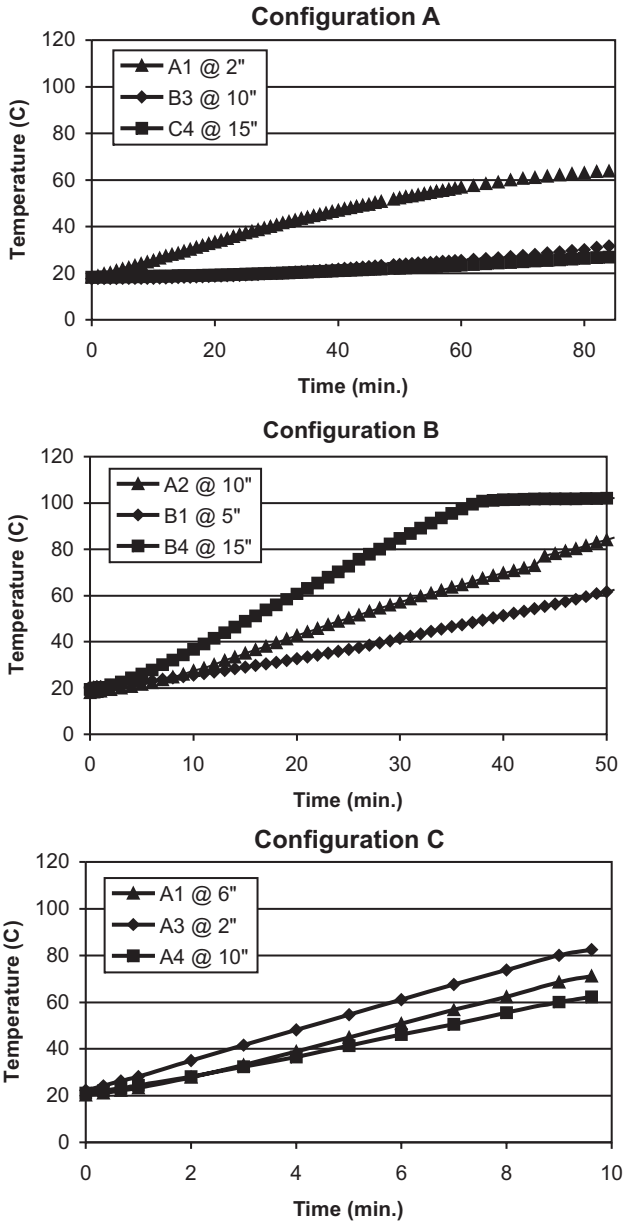

Figure 3. — Time vs. temperature plots for three configurations depicted in Figure 5 showing differences due to power, volume, and shadowing effects. Configuration a) was irradiated at 1 kW, and Configurations b) and c) at 3 kW.

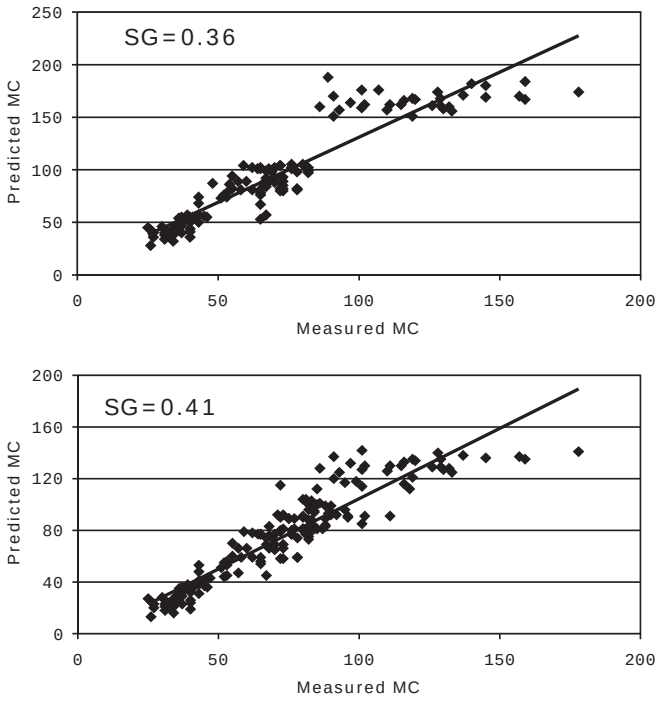

Figure 4. — Relationship between predicted vs. measured MC of wood based on two estimated SG values of 0.36 (top) and 0.41 (bottom).

Table 3. — Summary of nematode experiments treated in the batch microwave system.

Wood temperature (°C)	Total number of wood samples	Samples (%) containing live nematodes (*n*)
25 (controls)	18	100 (18)
< 62	5	40 (2)
62	29	7 (2)
> 62	66	0 (6)

Table 4. — Mean nematode mortality by wood temperature during batch microwave processing in which both live and dead nematodes were counted (n = 48).[a]

Wood temperature (°C)	Mean nematode mortality (%)	Standard deviation
25 (controls)	77a	28.7
< 62	33.3a	26.7
62	26.7b	57.7
> 62	100c	0

[a] Mean mortality percentages followed by the same letter were not significantly different at the $p < 0.05$ level.

0.36 (linear regression: F = 986; df = 1,68; $p < 0.0001$, $r^2 = 0.85$; F = 768; df = 1, 123; $p < 0.0001$; $r^2 = 0.86$, respectively). Thus, by adjusting the predicted MC values obtained with Equation [**1**] with the following linear equations, MC can be predicted with an accuracy of 85 to 86 percent (**Fig. 4**):

$$\text{SG} = 0.41, \text{adjusted predicted MC} = 14.4 + 0.78 \times (\text{predicted MC}); \quad [2]$$

$$\text{SG} = 0.36, \text{adjusted predicted MC} = 7.2 + 1.24 \times (\text{predicted MC}) \quad [3]$$

Batch processing of wood samples with a 6 kW, 2.45-GHz generator produced 100-percent morality in all treated red pine materials (4- by 4- by 20-in cant samples) infested with cerambycids at or above measured wood temperatures of 62°C, regardless of wood MC. No control larvae died, and they pupated normally. At this same temperature, however, some nematodes survived in red pine samples (**Table 3**). Thus, the temperature must exceed 62°C to obtain 100-percent mortality of nematodes (**Table 4**). All controls contained live nematodes with percent recovery of alive and dead nematodes of 29 ± 3

percent (range 9% to 66%). The recovery of nematodes from treated samples was 17 ± 1.3 percent (range 6% to 31%). These recovery rates are considered typical; for example, recovery of nematodes from soil rarely exceeds 20 percent (Barbercheck 2005). For a subset of 20 samples, all recovered nematodes (alive and dead) were counted, and no correlation was seen between percent mortality and percent recovery (p = 0.729), nor was there a relationship between percent recovery and live nematodes (p = 0.222), indicating that there was no bias in the recovery of live vs. dead nematodes.

Table 5. — Wood temperatures and mortality of larvae (L) and nematodes (N) by continuous microwave treatment of 1- by 4- by 20-inch boards.

Run	L or N	Average green weight of sample[a]	MW power	Chamber air temp.	No. of boards	Internal wood temp. range	Surface wood temp. range	No. of L or N alive after treatment
		(g)	(kW)	(°C)		- - - - - - (°) - - - - - -		
Control	N		0	25	4	na	na	2 to 12
1	N	975a	6	110	10	74 to 95	44 to 61	0
2	N	1222b	7	33	10	53 to 69	40 to 50	0
3	N	1455c	7	110	10	54 to 66	41 to 47	0
4	L	983a	5	110	10	70 to 91	42 to 58	0
5	L	978a	6	33	20	53 to 95	na	0
6	L	996a	6	110	10	69 to 94	46 to 58	0
7	L	1181b	6	110	10	58 to 88	45 to 66	0
8	L	1202b	7	33	10	46 to 86	38 to 47	0
9	L	1349c	7	110	10	51 to 72	40 to 46	0

[a] a = medium green weight; b = high green weight; c = very high green weight groups.

With batch processing, the higher the temperature, the higher the mortality (linear regression: F = 14.5, df = 1,46, p = 0.0004; equation: arcsin(mortality) = 0.91 + 0.0077 × (temp); r^2 = 0.24). Also, mortality was significantly higher in wood samples that reached 62°C or above compared to untreated controls (analysis of variation followed by orthogonal contrasts, p = 0.0002). As expected, as MC increased, the time required for wood samples to reach 62°C increased (linear regression: F = 158; df = 2, 146; $p < 0.001$; r^2_{adj} = 0.68). The MC of treated wood did not affect the percent recovery of nematodes (r^2 = 0.11, F = 3.5, df = 1, 28; p = 0.0721), suggesting that this relationship should hold for high, medium, or low MCs. This is likely due to the fact that the nematodes were only left in the wood (treated or untreated) for a maximum of 48 hours.

Position of the temperature probes along the wood sample had a minor effect on time required to reach 62°C. Positions 2 and 4 inches away from the end of the board reached 62°C more slowly than positions 6 and 8 inches away from the end of the board (Equations: log(time)sec = 2.42 + 0.605 × (MC); log(time)sec = 1.825 + 0.605 × (MC), respectively). The slope of the time required to reach 62°C was the same regardless of position of the probe, but the intercepts were significantly different. Since the samples were stationary in the batch microwave system, the microwave field intensity varied within the chamber and distribution of MC within each board likely varied, contributing to the slight differences in time to reach this temperature along the length of the boards.

Continuous microwave experiments

Despite the fact that not all 1- by 4- by 20-inch wood samples reached the target internal temperature of 62°C in any of the MC groups (**Table 5**), continuous microwave energy killed 100 percent of nematode and larval samples. Live nematodes and larvae were recovered from all control samples. Core wood temperatures as low as 46° and 53°C were still lethal to larvae and nematodes, respectively. These lower temperature requirements may be due to the movement of the sample through the chamber, thus exposing the sample to a more uniform microwave field. Additional trials conducted on 4- by 4- by 4-inch wood cubes also produced nearly 100-percent mortality of cerambycid larvae at lower temperatures when the samples were rotated on a turntable compared to samples that remained stationary during microwave treatment (data not shown). These trials were conducted in a separate noncommercial scale 2.45-GHz microwave unit. Nematode mortality in counted samples treated with 7 kW of power in a heated 110° or 33°C chamber was significantly greater than untreated controls (χ^2 = 26.5, df = 1, $p < 0.001$ and χ^2 = 15.2, df = 1, p = 0.001). However, the wood used in these trials were of different average MCs, so direct comparisons between heated and unheated chambers could not be made, but will be tested in the future.

When data for all wood MCs were combined, MC prior to treatment with continuous microwave energy was negatively correlated with internal wood temperature (linear regression: F = 16.5; df = 1,68; p = 0.0001). When wood was sorted by MC for analysis (medium, high, and very high), however, green weight was not predictive of internal wood temperature, especially for wood of very high MC (F = 0.47; df = 1,18; p = 0.502; mean internal temperature = 58.5° ± 1.2°), which in part may be due to smaller sample sizes when groups were analyzed separately. For the medium and high MC wood groupings, although there was a negatively correlated trend, MC was not significantly predictive of internal temperature (medium MC: F = 1.82; df = 1, 18; p = 0.194; high MC: F = 1.79; df = 1,28; p = 0.194). Despite these findings, the mean internal temperature of medium and high MC samples exceeded the target of 62°C (69.8° ± 2.50° and 65.2° ± 1.98°C, respectively). Low temperatures recorded for some samples may occur if total MC load in the chamber is influenced by the total MC load from all of the boards combined, not just by the MC of each individual board. For future experiments we intend to investigate this hypothesis.

Conclusions

Wood temperatures greater than 62°C are lethal to pine wood nematodes and cerambycid larvae infesting red pine in a chamber in which the wood samples remain stationary. These preliminary findings also suggest, however, that nematodes or larvae in lumber in which the microwave field is continuously moving, either by rotation or on a conveyor belt, die at lower wood temperatures than in a batch system without movement. Additional experiments with non-stationary, commercial equipment are recommended to investigate this phenomenon further. Additional assessment of the effects of conventionally heated vs. non-heated microwave chambers on lethal micro-

wave doses would also be helpful for the commercialization and regulatory process.

In the batch experiments where MC load and microwave input power were fixed, increased wood MC increased the microwave exposure time required to reach 62°C. Thus, separation of lumber by MC may be necessary to reduce the energy input required to reach 100-percent mortality during batch processing. Untreated red pine lumber can be grouped by estimated MC using Equations [**1**] and [**2**] or [**3**], as long as the green weight and the volume of the board are known. Similar equations can be developed for other wood species. Additional experiments are planned to test this separation method further.

From this study, it can be concluded that commercial microwave treatment (2.45 GHz) of 1-inch thick red pine lumber infested with cerambycids or pine wood nematodes is a feasible alternative to conventional kiln ovens or methyl bromide fumigation for phytosanitation.

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