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Mortality of Bark- and Wood-boring Beetles (Coleoptera: Buprestidae, Cerambycidae, and Curculionidae) in Naturally Infested Heat-treated Ash, Birch, Oak, and Pine Bolts

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Abstract

Firewood and wood packaging material (WPM) are major pathways for moving bark- and wood-infesting insects (borers). Heat treatment regulations for interstate firewood movement vary among U.S. states: from 56°C for 30 min to 71.1°C for 75 min. Current WPM international standards (ISPM 15) require heating to a minimum of 56°C for 30 min throughout the profile of the wood. Using bolts from infested ash (*Fraxinus*), birch (*Betula*), oak (*Quercus*), and pine (*Pinus*) trees in Michigan, we assessed borer mortality at core temperatures of 50, 53, 56, and 60°C maintained for 30 min in chambers set to 60, 65, 70, or 75°C. After treatment, bolts were monitored for adult emergence and later dissected to determine borer mortality rates. Mortality was high to complete for all heat treatments and increased with both increasing core and chamber temperatures. For the *Agrilus* (Buprestidae) species tested, there was complete mortality of *Agrilus anxius* on birch and *Agrilus planipennis* on ash when core temperatures of 56°C or higher were targeted regardless of chamber temperature. However, on oak, a few *Agrilus bilineatus* and *Agrilus sulcicollis* survived in bolts heated to 56°C in chambers at 60 and 65°C, and some *A. sulcicollis* survived in chambers set at 70 and 75°C. Similarly, a few pine-infesting borers survived heating to 56°C at all chamber temperatures. However, there was complete mortality in all hosts when bolts were heated to 60°C for 30 min, regardless of chamber temperature. Results are discussed in terms of current treatment regulations for firewood and WPM.

Key words: heat sterilization, phytosanitary treatment, ISPM 15, wood borer, bark beetle

Many bark- and wood-infesting insects (borers) can be moved inadvertently both within countries and internationally in products such as firewood and wood packaging material (WPM) (Haack et al. 2010, 2014; Rassati et al. 2018, Meurisse et al. 2019, Solano et al. 2021). In the United States, current regulations for interstate movement of firewood are variable but the National Plant Board recommends heating firewood of all species to a core temperature of 60°C for 60 continuous min (NPB 2020, Downs and Greenwood 2022). The current international heat-treatment requirement (ISPM 15) for wood packaging materials (WPM, e.g., pallets and crating) used in international trade requires heating to a minimum of 56°C for 30 continuous min throughout the profile of the wood, including the core (IPPC 2019). The heat treatment standard for ISPM 15 was based largely on the lethal temperature (52.1°C) determined for the pinewood nematode [*Bursaphelenchus xylophilus* (Steiner & Buhrer) Nickle; Aphelenchida: Parasitaphelenchidae] and its vectors in the genus Monochamus (Coleoptera: Cerambycidae) (Allen et al. 2017).

After the discovery of the emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae), in southeastern Michigan in 2002, there was concern that this borer could be inadvertently moved in firewood and WPM as well as logs and nursery stock (Haack et al. 2014, 2015; Haack and Petrice 2021; Meurisse et al. 2019, MacQuarrie et al. 2020). Several researchers have tested the thermal limits of *A. planipennis* using various temperature and time combinations (McCullough et al. 2007, Nzokou et al. 2008, Myers et al. 2009, Goebel et al. 2010, Sobek et al. 2011), with the study by MacQuarrie et al. (2020) testing temperatures and methods closest to ISPM 15 standards.

The regulations developed for heat treating firewood and WPM specify the temperature that must be reached throughout the entire profile of the wood, including its core, and doing so by monitoring the largest wood pieces treated during each heating cycle (IPPC 2019, NPB 2020). These regulations, however, do not require a minimum chamber temperature that should be used by kiln operators. There is great variability in the air temperatures used in conventional heat chambers to heat firewood and WPM, often depending on the kiln size, energy source, if steam is added, moisture content of the wood, and season of the year. The heating conditions at WPM facilities are routinely set at 70–80°C, and at times much higher (Simpson et al. 2003, Wang 2010, Brad Gething, National Wooden Pallet and Container Association, pers. comm.). For facilities that heat treat firewood, large-scale producers usually heat at chamber temperatures of 70°C and above, however, equipment available to some small-scale producers may not be able to reach 70°C (Wang et al. 2009, 2011, 2014, USDA APHIS 2011. NPB 2020, Xiping Wang, USDA Forest Products Laboratory, pers. comm.).

Despite the adoption of ISPM 15, live wood borers are occasionally detected in WPM marked as compliant with ISPM 15 (Haack et al. 2014, Eyre and Haack 2017, Wu et al. 2017, Eyre et al. 2018). Several reasons have been suggested as to why live borers could occur in treated WPM (Haack et al. 2014), including borer tolerance of the treatment, posttreatment colonization by borers, poorly calibrated equipment, and fraud, among others.

There were two main objectives in the current study. The first was to heat treat borer-infested bolts from different tree species and monitor borer survival after heating to various core temperatures, including 50, 53, 56, and 60°C. The second objective was to evaluate how various chamber temperatures (e.g., 60, 65, 70, and 75°C) affected borer mortality for the core temperatures tested. Core temperatures of 56 and 60°C were tested for each tree species, with 50 and 53°C tested if there was a large supply of host material. As for the chamber air temperatures, we selected 65, 70, and 75°C because they bracket the conditions used in many commercial operations, while 60°C was chosen more for experimental purposes as a lower limit.

Methods and Materials

Sample Selection and Bolt Handling

We conducted several studies from 2009 to 2013, using small-diameter, naturally infested trees found throughout Lower Michigan. The target borers in the three hardwood genera selected (*Betula* = birch, *Fraxinus* = ash, and *Quercus* = oak) were all buprestids in the genus *Agrilus*, which includes several important tree-killing species (Herms and McCullough 2014, Petrice and Haack 2014, Haack and Petrice 2019). For *Agrilus anxius* Gory (bronze birch borer), we used 14 infested *Betula pendula* Roth (European white birch; DBH = 10–20 cm) trees. For *Agrilus bilineatus* (Weber) (twolined chestnut borer), we used 12 *Quercus rubra* L. (northern red oak; DBH = 25–35 cm) trees. For *Agrilus planipennis* Fairmaire (emerald ash borer), we used 43 infested *Fraxinus pennsylvanica* Marshall (green ash; DBH = 17–28 cm) trees. For *Agrilus sulcicollis* Lacordaire (European oak borer), we used 19 infested *Q. robur* L. (English oak; DBH = 20–35 cm) trees. These four *Agrilus* species have similar life histories, being typically univoltine, having four larval instars, and overwintering mostly as last instars (J-larval stage) in pupal cells constructed in the outer sapwood for trees with thin bark and both the outer sapwood and outer bark in thicker barked trees (Haack and Benjamin 1982, Muilenburg and Herms 2012, Petrice and Haack 2014, Haack et al. 2015). For the one conifer selected, *Pinus resinosa* Sol. ex Aiton (red pine; DBH = 18–28 cm; 8 trees), we targeted primarily bark beetles (Curculionidae: Scolytinae) in the genus *Ips*, woodboring weevils in the genus *Pissodes* (Curculionidae), and longhorned beetles (Cerambycidae) in the genera *Acanthocinus* and *Monochamus*. The *Acanthocinus*, *Ips*, and *Pissodes* larvae typically complete their development in the inner and outer bark tissues, whereas *Monochamus* larvae begin development in the inner bark and outer sapwood tissues and later complete development deeper in the sapwood (Drooz 1985).

Bolts from the hardwood trees were collected during the winter months (December–March) when most *Agrilus* individuals were overwintering in the J-larval stage within pupal cells constructed primarily in the outer sapwood. In the tests with red pine, we collected bolts during the warmer months of summer and early autumn (June–September) when most borers were larvae, and prior to emergence of brood adults for any bark beetles present.

Before cutting the bolt sections, we removed the outer bark in a few areas of the trunk to identify portions that were heavily infested with the target borers. Bolts were then cut from the infested trunks, usually at lengths of 30–40 cm, depending on the tree species and branching pattern. We selected areas of the trunk that were free of branches, scars, and major crooks, so that each bolt selected was generally straight and cylindrical in shape. The diameter of the selected bolts ranged from 7 to 22 cm, which covers the range of sizes of individual wood pieces found in a typical block pallet.

After cutting, bolts were transported to our laboratory on the Michigan State University campus in East Lansing, MI. The bolts were labeled with information on species, tree number, and cutting date, and then stored in a walk-in cooler (≈4–5°C). One to two days prior to treatment the bolts were removed from cold storage and acclimated to room temperature. Depending on the cutting date, the hardwood bolts were kept in cold storage for 1–3 months to ensure a sufficiently long cold exposure to meet diapause requirements prior to pupation. However, pine bolts were kept in cold storage for no more than 1–3 weeks before treatment.

Bolt Handling before Testing

The dimensions of each bolt were recorded including length and diameter (maximum thickness for split bolts). Bolt diameter included the outer bark and was recorded at both cut ends and then averaged. Two thermocouples (30-gauge T-type; Cole-Parmer, Vernon Hills, IL) were inserted into each bolt along its midpoint, one to a depth of 1 cm within the sapwood and the other to the center of the bolt, with depth depending on bolt diameter or thickness for split bolts. The 1-cm depth was selected because many *Agrilus* larvae overwinter and pupate in the outer sapwood (Chamorro et al. 2015, Petrice and Haack 2014, Zang et al 2017). We first drilled a hole to the appropriate depth with a handheld cordless drill using a bit size of 7/64 inch (=2.8 mm). The tip of the thermocouple was inserted to the bottom of the drill hole. Fine sawdust was packed in the drill hole to fill any voids and then a toothpick was inserted alongside the thermocouple to snugly hold it in place and further seal the drill hole. The toothpick was then broken off at the outer bark surface and the entire area was covered with a small amount of 'plumber's putty' (Plubset Putty, La-Co Industries, Elk Grove Village, IL) to prevent outside air from entering and affecting the temperature measurement.

Heat-Treatment Procedure

We used a Lunaire Steady State Chamber (Lunaire Environmental; New Columbia, PA) with a 32 ft³ capacity (0.9 m³) to heat the bolts. The chamber had a Watlow F4 programable temperature controller (Watlow Inc., Winona, MN), which was set to increase the chamber temperature by a ramp rate of 1°C per minute and then remain at the selected target temperature for the remainder of the run. Relative humidity was not regulated in the chamber, therefore the conditions tested were considered as a 'dry-heat schedule' (Wang et al. 2009). The two thermocouple wires from each bolt were fed through a special wall opening on the Lunaire chamber (which was later sealed before heating) and then connected to a 20 channel datalogger (Graphtec midi Logger GL800; Graphtec Corp.; Yokohama, Japan). The dataloggers recorded temperature once per minute.

Up to 10 bolts were treated at the same time, utilizing two shelves in the chamber. Although multiple bolts were often tested together, they were handled separately and considered independent. Each bolt was monitored individually. The time when the core temperature first reached the target temperature was recorded. Each bolt was removed from the chamber after its core remained at or above the core temperature for 30 continuous min. Bolts could be removed quickly and this action had no noticeable effect on the internal wood temperatures in any remaining bolts. After removal from the chamber, bolts were placed on a laboratory bench to cool to ambient conditions, and the internal core temperature continued to be monitored to determine how long the core remained above the target temperature.

Bolt Handling Posttreatment

After cooling, bolts were placed in individual cardboard tubes (ca. 20–25 cm diameter, 66 cm length; Michigan Can and Tube, Saginaw, MI) for rearing. Plastic lids with fine screening for ventilation were placed on the tube ends, and a clear collection cup was attached near the center of each lid to capture emerging insects (Petrice and Haack 2006). Tubes were laid horizontally on shelves in the laboratory and checked twice weekly for adult emergence. Any adults found were placed in labeled vials and frozen until examined and counted later. The indoor air temperature was 22–24°C. Depending on tree species and the borers expected to be present, the bolts generally remained in the tubes for 1–3 months to allow most borers to complete development and emerge. After about three weeks with no new adult borers emerging, we stopped the study and inspected the interior of each tube for dead insects that failed to reach the collection cups. The number of emerged adults was recorded by species for each bolt.

Next, the outer bark of each bolt was removed with a drawknife and bolts were examined for borers and their galleries near the inner bark-sapwood interface. For larval galleries that entered the sapwood (usually the cerambycids), we split the bolt repeatedly with a hydraulic splitter, and followed each gallery to its end. We recorded the number of borers found inside each bolt by taxa (i.e., identifying to the species or family level depending on which life stages were found and certainty of identification), life stage, and if the individuals appeared alive or dead, usually based on movement or color (i.e., larval body white and soft = live; larval body tan/brown and rigid = dead).

Heat Treatment Schedules

We did not have enough infested host material to test bolts from every tree species at all combinations of core temperature and chamber temperature. At a minimum, we targeted core temperatures of 56 and 60°C for each tree species tested because these treatment temperatures were important in current firewood and WPM regulations (IPPC 2019, NPB 2020). If additional host material was available, we tested lower core temperatures (50 and 53°C) to determine how borer survival was affected.

A. planipennis was our initial target borer, and thus it was the focus of most studies. We tested core temperatures of 50, 53, 56, and 60°C for 30 continuous min. At 56°C, which is the requirement for ISPM 15 (IPPC 2019), we tested bolts that were whole or split longitudinally. When targeting core temperatures of 50, 53, and 56°C, we tested each at chamber temperatures of 60, 65, 70, and 75°C (Table 1 and Supp Table S1 [online only]). However, when targeting a 60°C core temperature, we tested chamber temperatures of 65, 70, and 75°C (Table 1 and Supp Table S1 [online only]). In each of the above studies, and those listed below as well, several (10–33) bolts from the same treatment cohort were not heat treated to serve as controls (Tables 1–3). Efforts were made to distribute bolts from each infested tree that we used across all core and chamber treatments.

The various core and chamber temperature combinations tested for the other *Agrilus* and pine-infesting borers are listed in Tables 2 and 3 and Supp Table S2-S3 (online only). Briefly, for *A. anxius*, we targeted 56°C core temperature at chamber temperature of 65, 70, and 75°C, and 60°C core temperature at chamber temperatures of 70, and 75°C. For *A. bilineatus* we targeted 50 and 56°C core temperatures at chamber temperatures of 60, 65, 70, and 75°C, as well as a 60°C core temperature at chamber temperatures of 65, 70, and 75°C. For *A. sulcicollis*, we targeted 53 and 56°C core temperatures at chamber temperatures of 60, 65, 70, and 75°C, as well as 60°C core temperature at chamber temperatures of 65, 70, and 75°C. For the pine-infesting borers, we targeted 56°C core temperature at chamber temperatures of 60, 65, 70, and 75°C, as well as 60°C core temperature at chamber temperatures of 65, 70, and 75°C.

Data Analyses

For each core-chamber temperature combination where hardwood-infesting *Agrilus* species were tested, percentage survival for each *Agrilus* species was compared among chamber temperatures, and the associated control bolts for each core treatment using a generalized linear model (GLM) with a beta distribution and a logit link function (PROC GLIMMIX, SAS 9.4). Survival was based on live adults that emerged as well as live individuals found during bolt dissection. Bolt diameter was used as a covariate in the survival analyses. When the covariate interaction term, bolt diameter*chamber temperature was significant, an unequal slopes GLM model was used to evaluate effects of chamber temperature at the 10th percentile, mean, and 90th percentile along the covariate. Percentage survival could not be accurately calculated for the pine-infesting borers because of the difficulty recovering and identifying all dead insects during bolt dissections. Live *Agrilus* and pine-borer post-treatment densities were compared among chamber temperatures and the associated control bolts for each core treatment using a generalized linear model with a lognormal distribution and the identity link function. Bolt diameter was not used as a covariate in the borer density analyses because live borer densities were standardized using bolt surface area prior to analysis. Only those chamber temperature treatments where some survival occurred were included in the analyses. No analyses were conducted when there was complete mortality for all chamber temperature treatments for a particular core temperature. Bolts from more than one core temperature treatment were included in the same model when multiple core temperature treatments shared the same cohort of control bolts (i.e.,

Table 1. Summary data for *Agrilus planipennis* (emerald ash borer, EAB) survival in *Fraxinus pennsylvanica* (green ash) bolts heated to various core temperatures for 30 continuous min, using constant chamber temperatures of 60–75°C

		Bolt data (mean ± SE)						Mean (±SE) maximum temp. during heating cycle (°C)	
Target core temp. (°C)	Chamber temp. (°C)	Bolt whole or split	Number	Live EAB (emerged + dissected)/m²	Total EAB (live + dead)/m²	Survival (%)	Percentage of bolts with live borers	Temp. at 1-cm depth in sapwood	Temp. at bolt core
50	60	Whole	10	13.0 ± 4.4a	67.8 ± 7.4	20.6 ± 7.2 b	70.0	54.6 ± 0.2d	51.7 ± 0.1d
50	65	Whole	8	0.9 ± 0.9b	81.3 ± 13.9	1.3 ± 1.3 b	12.5	58.3 ± 0.3c	52.8 ± 0.2c
50	70	Whole	10	0	64.4 ± 11.3	0	0	63.5 ± 0.4b	54.6 ± 0.2b
50	75	Whole	9	0	64.2 ± 11.6	0	0	64.1 ± 0.6a	56.0 ± 0.3a
Control	Ambient	Whole	10	42.2 ± 5.9a	55.7 ± 9.0	79.0 ± 4.3 a	100		
				$F = 36.43$		$F = 6.39$		$F = 98.44$	$F = 87.32$
				df = 2,10		df = 2,22		df = 3,33	df = 3,33
				$P < 0.0001$		$P = 0.0065$[a]		$P < 0.0001$	$P < 0.0001$
53	60	Whole	10	2.3 ± 1.5b	68.8 ± 16.4	12.2 ± 10.0 b	20.0	56.6 ± 0.2d	54.0 ± 0.1d
53	65	Whole	10	0	62.0 ± 12.5	0	0	59.6 ± 0.3c	55.5 ± 0.1c
53	70	Whole	9	0	66.4 ± 15.3	0	0	62.7 ± 0.4b	56.9 ± 0.2b
53	75	Whole	10	0	53.7 ± 10.2	0	0	65.4 ± 0.4a	57.8 ± 0.1a
Control	Ambient	Whole	10	35.5 ± 5.0a	54.0 ± 9.9	77.2 ± 8.4 a	100		
				$F = 45.47$		$F = 11.99$		$F = 127.52$	$F = 175.18$
				df = 1,9		df = 1,18		df = 3,35	df = 3,35
				$P < 0.0001$[b]		$P = 0.0028$		$P < 0.0001$	$P < 0.0001$
56	60	Whole	33	0	64.1 ± 8.1	0	0	57.5 ± 0.1d	56.4 ± 0.0d
56	65	Whole	38	0	70.7 ± 8.9	0	0	60.1 ± 0.1c	57.5 ± 0.1c
56	70	Whole	35	0	62.1 ± 7.4	0	0	62.3 ± 0.2b	58.1 ± 0.1b
56	75	Whole	40	0	67.2 ± 8.6	0	0	65.4 ± 0.3a	60.0 ± 0.1a
Control	Ambient	Whole	37	54.5 ± 6.0	83.2 ± 9.1	70.0 ± 4.7	97.3		
								$F = 281.97$	$F = 42.84$
								df = 3,142	df = 3,142
								$P < 0.0001$	$P < 0.0001$
56	60	Split	12	0	23.6 ± 6.9	0	0	56.4 ± 0.1c	56.4 ± 0.1d
56	65	Split	16	0	18.6 ± 3.1	0	0	59.8 ± 0.4b	57.3 ± 0.1c
56	70	Split	17	0	19.4 ± 4.1	0	0	60.8 ± 0.4b	58.0 ± 0.2b
56	75	Split	15	0	15.5 ± 1.9	0	0	64.0 ± 0.3a	59.7 ± 0.3a
Control	Ambient	Split	16	16.1 ± 3.1	19.7 ± 3.5	81.3 ± 5.7	100		
								$F = 62.81$	$F = 48.11$
								df = 3,56	df = 3,56
								$P < 0.0001$	$P < 0.0001$
60	65	Whole	7	0	16.6 ± 3.5	0	0	62.0 ± 0.4c	60.4 ± 0.1
60	70	Whole	7	0	39.9 ± 7.6	0	0	64.8 ± 0.4b	61.6 ± 0.2
60	75	Whole	8	0	29.5 ± 7.5	0	0	66.4 ± 0.3a	62.9 ± 0.2
Control	Ambient	Whole	9	14.9 ± 3.0	28.2 ± 5.5	56.3 ± 6.8	100		

Table 1. Continued

Target core temp. (°C)	Chamber temp. (°C)	Bolt data (mean ± SE)					Mean (±SE) maximum temp. during heating cycle (°C)	
		Bolt whole or split	Number	Live EAB (emerged + dissected)/m²	Total EAB (live + dead)/m²	Survival (%)	Percentage of bolts with live borers	Temp. at 1-cm depth in sapwood	Temp. at bolt core
								$F = 39.41$ df = 2,19 $P < 0.0001$	$F = 60.54$ df = 2,19 $P < 0.0001$

GLM (generalized linear models) results are given within each core treatment. Means with the same letters are not significantly different ($P < 0.05$). The Kenward-Roger denominator degree of freedom method was used. No statistical tests were conducted when there were no survivors in all treatments for a particular host and target core temperature.
[a]Covariates 'diameter' and 'diameter*chamber temperature' were significant.
[b]Group function used to adjust for homogeneity of variance violation.

A. bilineatus 50 and 56°C core temperatures, and *A. sulcicollis* 53, 56, and 60°C core temperatures). For each *Agrilus* and pine-borer core treatment test, bolt diameter and length (cm), maximum internal bolt temperature at 1 cm and at the core (°C), time to reach the target core temperature (min), temperature rise-rate to the target core temperature (°C/min), and time the internal core temperature remained above the target core temperature after removal from the chamber (min) were compared among chamber temperatures using a generalized linear model with the normal distribution and identity function. Residuals were evaluated for normality and homogeneity of variance. When the homogeneity of variance assumption was violated, the group option was added to the SAS code to account for the unequal variances. Degrees of freedom for all models were calculated using the Kenward-Roger denominator degrees of freedom option (Brown and Prescott 2006). Least-squared means that were significantly different ($P < 0.05$) were separated using the Tukey-Kramer multiple comparisons tests.

Results

For all borers tested, survival decreased with increasing core temperature and increasing chamber temperature (Tables 1–3). Below are details from each study. To improve readability, means, standard error values, and most statistical tests results for key borer and temperature data are presented in Tables 1–3 and not in the text. Similarly, additional bolt and temperature data, along with associated statistical tests results, are mostly given in Supp Tables S1–S3 (online only). Within a given test using bolts of the same host and target core temperature, mean bolt diameter did not differ significantly (statistical results ranged from: $F = 1.82$; df = 4,44; $P = 0.142$ to $F = 0.29$; df = 8,72; $P = 0.968$; Supp Tables S1–S3 [online only]). However, bolt diameter and the interaction of bolt diameter × chamber temperature were significant covariates on two occasions, once for *A. planipennis* survival at the target core temperature of 50°C (Table 1; bolt diameter: $F = 10.52$; df = 1,22, $P = 0.0037$; bolt diameter × chamber temperature: $F = 7.48$, df = 2,22, $P = 0.0033$) and once for *A. sulcicollis* survival at the target core temperatures of 53 and 56°C (Table 2; diameter: $F = 6.38$, df = 1,49, $P = 0.0148$; bolt diameter × chamber temperature: $F = 4.33$, df = 5,49, $P = 0.0024$). In each case, there was a tendency for larger-diameter bolts (i.e., diameters in the 90% percentile) to have lower survival at the lower chamber temperatures. This seems logical, given that at lower chamber temperatures it generally took longer to reach the target core temperature (Supp Tables S1–S3 [online only]).

A. planipennis

In the *A. planipennis* studies, posttreatment densities of live beetles ranged from 14.9–54.5 per m² for the control bolts (Table 1). There was some survival of *A. planipennis* in ash bolts treated to core temperatures of 50 and 53°C, but only at the lower chamber temperatures of 60 and 65°C (Table 1). At 50°C core temperature, emergence occurred in 7 of the 10 test bolts when the chamber temperature was 60°C, whereas emergence was only recorded from 1 of the 8 bolts tested when the chamber temperature was 65°C (Table 1). At core temperatures of 56 and 60°C, however, there was 100% mortality at all chamber temperatures tested (Table 1). Similarly, no *A. planipennis* emerged from any of the split bolts tested at 56°C core temperature (Table 1).

For all target core temperatures, the mean maximum temperature reached at the end of the 30-min heating period exceeded the target core temperature at both the core and the 1-cm depth into the sapwood (Table 1). Moreover, as chamber temperature increased so

Table 2. Summary survival data for *Agrilus anxius* in birch, *Agrilus bilineatus* in oak, and *Agrilus sulcicollis* in oak that were heated to various core temperatures for 30 continuous min, using constant chamber temperatures of 60–75°C

		Bolt data (mean ± SE)					Mean (±SE) maximum temp. during heating cycle (°C)	
Target core temp. (°C)	Chamber temp. (°C)	Number of bolts	Live beetles (emerged + dissected)/m²	Total beetles (live + dead)/m²	Survival (%)	Percentage of bolts with live borers	Temp. at 1-cm depth in sapwood	Temp. at bolt core
Agrilus anxius (bronze birch borer) on *Betula pendula* (European white birch)								
56	65	11	0	48.7 ± 14.0	0	0	60.4 ± 0.3b	58.5 ± 0.2b
56	70	23	0	51.6 ± 7.5	0	0	63.3 ± 0.3a	59.8 ± 0.2a
56	75	8	0	64.6 ± 15.9	0	0	64.6 ± 0.5a	60.1 ± 0.1a
							$F = 27.81$	$F = 9.58$
							df = 2,39	df = 2,39
							$P < 0.0001$	$P = 0.0004$
60	70	9	0	56.0 ± 14.7	0	0	64.9 ± 0.5b	62.3 ± 0.2a
60	75	9	0	56.7 ± 11.8	0	0	66.9 ± 0.5a	63.4 ± 0.1b
Control	Ambient	23	28.2 ± 4.7	37.8 ± 5.0	68.8 ± 6.9	87.0		
							$F = 8.15$	$F = 16.40$
							df = 1,16	df = 1,16
							$P = 0.0115$	$P = 0.0009$
Agrilus bilineatus (twolined chestnut borer) on *Quercus robur* (English oak)								
50	60	8	44.0 ± 14.2ab	76.3 ± 13.1	59.0 ± 12.2a	100	54.2 ± 0.2d	52.0 ± 0.2c
50	65	7	9.3 ± 5.2bc	70.9 ± 17.7	11.7 ± 5.7b	42.9	56.4 ± 0.5c	53.5 ± 0.5b
50	70	7	5.7 ± 4.4c	82.2 ± 28.9	3.6 ± 2.4bc	28.6	60.1 ± 0.4b	54.9 ± 0.3ab
50	75	8	0	57.2 ± 16.2	0	0	62.2 ± 0.3a	55.9 ± 0.6a
							$F = 104.98$	$F = 19.91$
							df = 3,26	df = 3,26
							$P < 0.0001$	$P < 0.0001$
56	60	10	0.8 ± 0.8c	91.1 ± 18.9	0.6 ± 0.6c	10.0	57.4 ± 0.2d	56.5 ± 0.1d
56	65	11	1.2 ± 1.2c	70.0 ± 14.4	0.9 ± 0.9c	9.1	60.5 ± 0.2c	57.9 ± 0.2c
56	70	10	0	95.7 ± 22.3	0	0	62.1 ± 0.6b	59.3 ± 7.2b
56	75	10	0	97.9 ± 22.8	0	0	65.4 ± 0.5a	61.7 ± 0.5a
Control	Ambient	10	52.9 ± 12.6a	66.0 ± 14.5	82.0 ± 8.5a	100		
			$F = 43.15$		$F = 19.53$		$F = 67.15$	$F = 61.48$
			df = 5,16		df = 5,29		df = 3,36	df = 3,36
			$P < 0.0001$[a]		$P < 0.0001$		$P < 0.0001$	$P < 0.0001$
60	65	10	0	24.6 ± 6.9	0	0	61.3 ± 0.4c	60.1 ± 0.5b
60	70	8	0	30.0 ± 9.1	0	0	63.8 ± 0.5b	61.5 ± 0.3ab
60	75	8	0	33.0 ± 7.8	0	0	66.4 ± 0.6a	62.7 ± 0.3a
Control	Ambient	13	34.0 ± 8.3	36.5 ± 8.1	91.7 ± 4.6	100		
							$F = 27.50$	$F = 10.51$
							df = 2,23	df = 2,23
							$P < 0.0001$	$P = 0.0006$
Agrilus sulcicollis (European oak borer) on *Quercus robur* (English oak)								
53	60	9	26.2 ± 13.7ab	122.7 ± 42.4	27.1 ± 7.9b	66.7	55.8 ± 0.2c	53.5 ± 0.1d
53	65	9	10.5 ± 5.3b	126.8 ± 20.2	6.9 ± 3.5c	44.4	56.1 ± 0.3c	54.5 ± 0.1c

Table 2. Continued

Target core temp. (°C)	Chamber temp. (°C)	Bolt data (mean ± SE)					Mean (±SE) maximum temp. during heating cycle (°C)	
		Number of bolts	Live beetles (emerged + dissected)/m²	Total beetles (live + dead)/m²	Survival (%)	Percentage of bolts with live borers	Temp. at 1-cm depth in sapwood	Temp. at bolt core
53	70	9	0	94.1 ± 34.5	0	0	59.5 ± 0.5b	55.6 ± 0.1b
53	75	9	0	182.6 ± 65.1	0	0	61.3 ± 0.7a	56.9 ± 0.3a
							$F = 35.44$	$F = 65.94$
							df = 3,31	df = 3,32
							$P < 0.0001$	$P < 0.0001$
56	60	9	0	116.0 ± 31.7	0	0	57.4 ± 0.2c	56.3 ± 0.1c
56	65	10	2.4 ± 1.6b	184.7 ± 42.0	1.7 ± 1.1c	20.0	58.9 ± 0.6bc	56.9 ± 0.2b
56	70	10	3.4 ± 2.4b	134.8 ± 24.2	1.7 ± 1.2c	20.0	59.5 ± 0.4b	57.5 ± 0.2b
56	75	9	0.9 ± 0.9b	103. ± 27.3	0.3 ± 0.3c	11.1	62.4 ± 0.5a	58.7 ± 0.2a
							$F = 18.66$	$F = 38.11$
							df = 3,33	df = 3,34
							$P < 0.0001$	$P < 0.0001$
60	65	6	0	193.8 ± 52.7	0	0	61.5 ± 0.2b	60.1 ± 0.1c
60	70	9	0	89.2 ± 35.4	0	0	62.4 ± 0.3b	61.0 ± 0.2b
60	75	9	0	78.1 ± 19.0	0	0	64.6 ± 0.3a	61.8 ± 0.3a
Control	Ambient	14	130.2 ± 26.2a	147.6 ± 30.3	89.7 ± 2.8a	100		
			$F = 39.19$		$F = 6.7$		$F = 32.93$	$F = 14.24$
			df = 5,17		df = 5,49		df = 2,20	df = 2,21
			$P < 0.0001$[a]		$P < 0.0001$[b]		$P < 0.0001$	$P < 0.0001$

GLM results are given within each core treatment for each *Agrilus* species. For some core treatments, control bolts were shared across more than one core treatment because all bolts were collected from the same trees. In these instances, control bolt data and all associated core temperature treatments were compared together, i.e., *A. bilineatus* 50 and 56°C; and *A. sulcicollis* 53, 56, and 60°C. Means with the same letters are not significantly different ($P < 0.05$). Degrees of freedom were calculated using the Kenward-Roger method. No statistical tests were conducted when there were no survivors in all treatments for a particular host and target core temperature (See Methods).

[a]Covariates 'diameter' and 'diameter*chamber temperature' were significant.

[b]Group function used to adjust for homogeneity of variance violation.

Table 3. Summary survival data for various borers (Cerambycidae and Curculionidae) in *Pinus resinosa* (red pine) bolts that were heated to various core temperatures for 30 continuous min, using constant chamber temperatures of 60–75°C

Target core temp. (°C)	Chamber temp. (°C)	Mean (± SE) live beetles per m² emerged or dissected and number of bolts in which each borer group were present (N)			Percentage (%) of bolts with live borers when present			Total No. of bolts	Mean (±SE) maximum temperature during heating cycle (°C)	
		Ips	*Pissodes*	Cerambycidae	*Ips*	*Pissodes*	Cerambycidae		Temp. at 1-cm depth in sapwood	Temp. at bolt core
56	60	8.1 ± 2.8 (18)b	0 (7)	2.7 ± 1.8 (14)b	38.9	0	14.3	21	57.1 ± 0.1d	56.4 ± 0.0d
56	65	5.4 ± 4.1 (21)b	0 (8)	0.7 ± 0.7 (11)b	14.3	0	9.1	21	59.1 ± 0.1c	57.4 ± 0.1c
56	70	20.1 ± 17.4 (20)b	0 (9)	0 (11)	25.0	0	0	21	61.2 ± 0.2b	58.8 ± 0.2b
56	75	0 (21)	0 (17)	0 (11)	0	0	0	21	63.7 ± 0.2a	60.1 ± 0.2a
Control	Ambient	505.4 ± 77.3 (22)a	17.3 ± 3.5 (15)	28.3 ± 5.8 (18)a	100	93.3	94.4	22		
		$F = 114.52$		$F = 47.91$					$F = 318.93$	$F = 159.23$
		df = 3,35		df = 2,43					df = 3,77	df = 3,77
		$P < 0.0001$[a]		$P < 0.0001$					$P < 0.0001$	$P < 0.0001$
60	65	0 (13)	0 (13)	– (0)	0	0	0	13	61.2 ± 0.2c	60.5 ± 0.1c
60	70	0 (14)	0 (14)	0 (2)	0	0	–	14	63.9 ± 0.3b	61.9 ± 0.2b
60	75	0 (12)	0 (14)	0 (4)	0	0	0	14	65.2 ± 0.4a	62.8 ± 0.8a
Control	Ambient	88.3 ± 28.0 (14)	245.8 ± 81.8 (15)	18.8 ± 3.5 (10)	100	100	100	15		
									$F = 36.41$	$F = 61.30$
									df = 2,38	df = 2,38
									$P < 0.0001$	$P < 0.0001$

GLM results are given within each core treatment. Means with the same letters are not significantly different ($P < 0.05$). Degrees of freedom were calculated using the Kenward-Roger method. No statistical tests were conducted when there were no survivors in all treatments for a particular host and target core temperature. *Ips* = *I. grandicollis* and *I. pini*; *Pissodes* = *P. approximatus*; Cerambycidae = *Acanthocinus* sp. And *Monochamus* sp.

[a]Group function used to adjust for homogeneity of variance violation.

did the mean maximum temperature at both internal bolt locations (Table 1). For example, for bolts where the target core temperature was 56°C, the mean maximum core and 1-cm readings after 30 min were 56.4 and 57.5°C at a chamber temperature of 60°C, respectively, compared with 60.0 and 65.4°C when the chamber temperature was 75°C (Table 1). The mean length of time that the core temperature remained above the 56°C target core temperature after the bolts were removed from the chamber ranged from 18 to 66 min for whole bolts and 13–47 min for split bolts (Supp Table S1 [online only]).

A. anxius

There was 100% mortality of *A. anxius* in birch bolts heated to core temperatures of 56 and 60°C at all chamber temperatures tested (Table 2). By comparison, an average of 28.2 ± 4.7 *A. anxius* adults emerged per m^2 from the control bolts (Table 2). After 30 min at or above the target core temperature of 56°C, the final mean core, and 1-cm readings ranged from 58.5–60.1°C and 60.4–64.6°C, respectively, and similarly, when the target core temperature was 60°C they ranged from 62.3–63.4°C and 64.9–66.9°C (Table 2). The mean length of time that the bolt core temperature remained above the target core temperature after removal from the chamber ranged from 33.5–56.4 min when the target was 56°C, and 39.2–53.0 min when the target was 60°C (Supp Table S2 [online only]).

A. bilineatus

Oak bolts infested with *A. bilineatus* were heated to core temperatures of 50, 56, and 60°C. For the control bolts, the mean number of *A. bilineatus* that emerged or were still alive under bark per m^2 were 52.9 for the 50°C and 56°C treatments and 34.0 for the 60°C treatment (Table 2). *A. bilineatus* adults emerged from bolts heated to core temperatures of 50 and 56°C, especially at chamber temperatures of 60 and 65°C (Table 2). However, at a chamber temperature of 75°C, there was complete mortality for both the 50 and 56°C target core temperatures (Table 2). Percentage *A. bilineatus* survival for all chamber temperatures was significantly lower for 50 and 56°C core temperatures, with the exception of 50°C core and 60°C chamber temperatures, compared to controls ($F = 19.53$; df = 5,29; $P < 0.0001$; Table 2). At the target core temperature of 60°C, there was complete mortality at all chamber temperatures (Table 2). After 30 min at or above the 50°C target core temperature, the mean maximum core, and 1-cm readings ranged from 52.0–55.9°C and 54.2–62.2°C, respectively, and when the target core temperature was 56°C they ranged from 56.5–61.7°C and 57.4–65.4°C, and when the target core temperature was 60°C they ranged from 60.1–62.7°C and 61.3–66.4°C (Table 2). The mean length of time that the bolt core temperature remained above the target core temperature after removal from the chamber ranged from 39–74 min at a core temperature of 50°C, 19–30 min at 56°C, and 14–51 min at 60°C (Supp Table S2 [online only]).

A. sulcicollis

Oak bolts infested with *A. sulcicollis* were heated to core temperatures of 53, 56, and 60°C. On average, 130.2 live *A. sulcicollis* per m^2 emerged or were dissected from control bolts, compared with 26.2 from bolts treated at 53°C core with a 60°C chamber temperature, and 10.5 from bolts treated at 53°C core with a 65°C chamber temperature (Table 2). At a target core temperature of 56°C, one to just a few adults emerged from one or two of the test bolts even at the higher chamber temperatures (Table 2). Nevertheless, percentage *A. sulcicollis* survival for all chamber temperatures was significantly lower for 53°C core temperature, compared to controls, and 56°C core temperature had the lowest survival ($F = 19.53$; df = 5,29; $P < 0.0001$; Table 2). There was 100% mortality at all chamber temperatures when the target core temperature was 60°C (Table 2). After 30 min at or above the target core temperature of 53°C, the final mean core and 1-cm readings ranged from 53.5–56.9°C and 55.8–61.3°C, respectively, and similarly ranged from 56.3–58.7°C and 57.4–62.4°C at 56°C, and 60.1–61.8°C and 61.5–64.6°C at 60°C (Table 2). Depending on the chamber temperature, the mean length of time that the bolt core temperature remained above the target core temperature after removal from the chamber ranged from 19 to 74 min at 53°C, 12 to 40 min at 56°C, and 27 to 33 min at 60°C (Supp Table S2 [online only]).

Borers on Pine

The diversity of borers varied among the pine bolts tested but usually contained the bark beetles *Ips grandicollis* (Eichhoff) and *Ips pini* (Say) (Scolytinae), the weevil *Pissodes approximatus* Hopkins (Curculionidae), and longhorned beetles in the genera *Acanthocinus* and *Monochamus* (Cerambycidae). Buprestid larvae (*Chrysobothris* sp.) were present in about 10% of the bolts (11 of 106 bolts) heated to a core temperature of 56°C, while none were found in the bolts (0 of 57 bolts) heated to 60°C. At the time of bolt dissection, almost all surviving bark beetles and weevils had emerged as adults but most surviving cerambycids and buprestids were still larvae. Therefore, the bark beetle and weevil data presented in Table 3 are based primarily on emerged adults, whereas primarily larval data are presented for the cerambycids. The buprestid data was not included in Table 3 given their uneven distribution among the test bolts.

For the control bolts used in the 56°C core temperature study, a mean of 505 per m^2 adult bark beetles emerged or were dissected, and 17.3 per m^2 adult weevils, and 28.3 per m^2 adult cerambycids emerged or live larvae when dissected (Table 3). After heating to a core temperature of 56°C, no live weevils emerged or were dissected at any chamber temperature, but a few bark beetles emerged or were dissected and a few live cerambycids were dissected from bolts heated in chambers set at 70°C and below (Table 3). However, at a chamber temperature of 75°C, there were no surviving bark beetles or cerambycids (Table 3). Overall, 25 buprestid larvae were found in the 11 bolts that had buprestids. Of these, some live larvae were present at each of the four chamber temperatures, varying from 100% (3 of 3) survival at a chamber temperature of 60°C to 9% survival (1 of 11) at a chamber temperature of 75°C.

For the control pine bolts used in the 60°C core temperature study, a mean of 88.3 adult bark beetles emerged per m^2 as well as 245.8 weevils and 18.8 live cerambycid larvae (Table 3). After heating to a core temperature of 60°C, no live bark beetles, weevils or cerambycids emerged or were dissected (Table 3). In fact, no living and very few dead cerambycid larvae were found in the heat-treated bolts upon dissection compared with the control bolts (Table 3). It is likely that most cerambycid larvae were very small at the time of treatment and those that died were not often found when the bolts were split and dissected a few months later, while those that survived were easily found because they continued to feed and increase in size. As stated above, no buprestid larvae, alive or dead, were found in the pine bolts tested at 60°C.

After 30 min at or above the target core temperature of 56°C, the final mean core and 1-cm readings ranged from 56.4–60.1°C and 57.1–63.7°C, respectively, and for a target core temperature of 60°C ranged from 60.5–62.8°C and 61.2–65.2°C (Table 3). Depending on the chamber temperature, the mean length of time that the bolt

core temperature remained above the target core temperature after removal from the chamber ranged from 16.9–53.4 min at 56°C, and 37.6–66.8 min at 60°C (Supp Table S3 [online only]).

Discussion

We found high to complete mortality of all *Agrilus* species, bark beetles, weevils, and cerambycids in the four tree genera tested when bolts were heated to a core temperature of 56°C at the various chamber temperatures (>90% on pine, >98% on oak, and 100% on ash and birch), and complete (100%) mortality of all borers at 60°C. When pine bolts were tested at 56°C, there was very high mortality of the cerambycids (>90%) and bark beetles (>96%), complete mortality of the weevils (100%), but only 56% mortality of the few buprestids that were found (14 of 25 *Chrysobothris* larvae were dead when bolts were dissected). Other researchers, using various methods, showed that heating to, or near, a target core temperature of 56°C was lethal to the bark beetles (Curculionidae: Scolytinae) *Hylurgus ligniperda* (Fabricius) (Pawson et al. 2019) and *Pityophthorus juglandis* Blackman (Mayfield et al. 2014) and the longhorned beetles (Cerambycidae) *Anoplophora glabripennis* (Motschulsky) (Myers and Bailey 2011), *Anoplophora nobilis* (Ganglbauer) (Wang et al. 2003), *Arhopalus ferus* (Mulsant) (Pawson et al. 2019), and *Tetropium fuscum* (Fabricius) (Mushrow et al. 2004).

Several studies have evaluated *A. planipennis* mortality when subjected to various heating conditions (McCullough et al. 2007, Nzokou et al. 2008, Myers et al. 2009, Sobek et al. 2011, MacQuarrie et al. 2020), but none matched exactly the conditions used in commercial operations where wood is heated to ISPM 15 specifications, including the present study. Moreover, the many differences among all these studies make direct comparisons difficult. For example, Sobek et al. (2011) tested 'naked' larvae; McCullough et al. (2007) tested larvae in small wood or bark chips; Nzokou et al. (2008) used infested whole bolts, Goebel et al. (2010) used split and whole bolts, Myers et al. (2009) used split bolts, and MacQuarrie et al. (2020) used sawn lumber from infested trees. In the studies by Myers et al. (2009) and Goebel et al. (2010), wood temperature was recorded at a standard depth of 3.5 cm and 2.5 cm into the sapwood, respectively, rather than the actual core. In those studies where bolts and lumber were used, only our study and Nzokou et al. (2008) monitored temperatures at the actual core of the test wood. Chamber temperature also varied greatly among studies: MacQuarrie et al. (2020) used 63°C when targeting 56°C at the core (Chris MacQuarrie, Natural Resources Canada, pers. comm.), Goebel et al. (2010) used 65°C, Myers et al. (2009) used 80°C and later lowered the chamber temperature once the target temperature was reached, and Nzokou et al. (2008) used 82°C.

Although we and others (Nzokou et al. 2008, Myers et al. 2009, Goebel et al. 2010) have documented limited borer survival in wood heat-treated to or near 56°C, MacQuarrie et al. (2020) used a systems approach to document *A. planipennis* mortality at various stages of WPM production. They found that over 99.5% of *A. planipennis* present in infested ash logs were removed during the initial steps of debarking, slabbing, and milling, and that none of the remaining individuals in the sawn wood survived heat treatment where the target temperature was 56°C for 30 min. In addition, recall that Goebel et al. (2010) and Myers et al. (2009) recorded the internal temperature at uniform depths of 2.5 and 3.5 cm into the sapwood, respectively, rather than the core, which was usually deeper. Therefore, *A. planipennis* mortality rates in these two studies would likely have been higher if they had recorded at the core because the heating cycle would usually have been longer to reach the same target temperature. Mayfield et al. (2014, Fig. 1) demonstrated that as bolt diameter increased, the final temperature of the outer sapwood also increased for any specific target core temperature.

There are major differences between the above experimental studies and commercial operations. For example, in the above studies the individual bolts of heat-treated wood were removed when each bolt reached the end of its 30-min treatment period. By contrast, in commercial operations, all wood remains in the kiln until all thermocouples have reached the target temperature for the required treatment time, after which the kiln temperature is reduced. Another common difference is that heating rates are often lower in most treatment facilities, so time to reach specific core temperatures would be much longer than in the above experimental studies. Chamber temperature and heating rates are highly variable depending on the kiln type (Wang et al. 2009, 2011, 2014; USDA APHIS 2011, NPB 2020). Therefore, in most commercial operations almost all WPM heat treated to ISPM 15 specifications would experience longer treatment times for a given target core temperature than in most of the experimental studies described above.

Sobek et al. (2011) demonstrated that *A. planipennis* has a heat shock response and can survive elevated temperatures especially when temperatures are increased slowly. Perhaps this phenomenon is partially responsible for higher survival rates for some borers in the current study. That is, for a given borer and target core temperature, survival was often higher at the lower chamber temperatures, suggesting that some borers were less thermotolerant at the higher chamber temperatures because of faster temperature rise-rates in wood. However, this possible phenomenon was confounded with higher final wood temperatures at the end of the 30 min treatment period and longer periods of time for the wood to cool after removal from the chamber (Supp Tables S1-S3 [online only]).

Although the heat treatment specified in ISPM 15 (56°C for 30 min) has not changed since its adoption in 2002 (IPPC 2019), other changes such as the debarking requirements for WPM adopted in 2009 (Haack et al. 2014, IPPC 2019) have likely reduced arrival rates of live pests in treated WPM. However, in the case of interstate movement of firewood within the United States, the federal rules for heat treating firewood have varied considerably (USDA APHIS 2011, 2016; NPB 2020). For example, in response to the destructive nature of *A. planipennis* and its rapid spread in the United States, all hardwood firewood from areas regulated for *A. planipennis* was initially required to be heat treated to a minimum core temperature of 71.1°C (160°F) for 75 min when transported outside of quarantined areas. Later, largely in response to the findings of Myers et al. (2011), the standard was lowered to 60°C (140°F) for 60 min (USDA APHIS 2011). The U.S. firewood industry favored this change because it reduced energy costs and recognized that many small-scale firewood producers had difficulty attaining chamber temperatures high enough to heat firewood to 71.1°C (USDA APHIS 2011). However, in early 2021, because of USDA's decision to deregulate *A. planipennis* (USDA APHIS 2020), the 60°C for 60 min specifications was no longer a federal requirement, which allowed individual states to set their own heat treatment specifications (Downs and Greenwood 2022). As a result, a patchwork of state regulations ensued for interstate firewood movement, with some states regulating only hardwood firewood while others regulated both conifer and hardwood firewood, and similarly some states required heating to 56°C for 30 min, others used 60°C for 60 min, and still others required 71.1°C for 75 min (NPB 2020). The National

Plant Board favors using 60°C for 60 min as a national standard for firewood (NPB 2020).

Our findings, indicate there will be very low borer survival rates in WPM treated to the current ISPM 15 requirement of 56°C for 30 min. Using a 60°C for 30 min requirement for WPM would likely result in complete or nearly complete mortality of most borers. Similarly, setting chamber temperatures in heat-treatment facilities at or above 70°C, which is common for commercial WPM facilities, would also increase mortality of any borers present. As for firewood, our results support the recommendation by the National Plant Board for a 60°C for 60 min treatment schedule (NPB 2020). In fact, our results suggest that a 60°C for 30 min requirement would be adequate to sanitize firewood for most borers.

Of course, borer survival can still occur in treated firewood and WPM, especially when equipment is not properly calibrated, or if cold pockets occur in kilns due to poor air circulation or improper stacking of the wood. Moreover, posttreatment colonization can occur by some groups of borers especially when bark remains (Haack and Petrice 2009), and some borers, such as many species of Bostrichidae (Coleoptera), can infest bark-free wood (Gerberg 1957, Peters et al. 2002). Nevertheless, simply gaining full compliance of all treatment regulations by the firewood and WPM industries would greatly reduce unwanted movement of most bark- and wood-infesting insects.

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Supplementary Data

Supplementary data are available at *Journal of Economic Entomology* online.

Table S1. Summary bolt and temperature data during tests of *Agrilus planipennis* (emerald ash borer, EAB) survival in *Fraxinus pennsylvanica* (green ash) bolts when heated to various core temperatures for 30 continuous min, using constant chamber temperatures of 60 to 75°C. GLM results are given within each core treatment. Means with the same letters are not significantly different ($P < 0.05$). Degrees of freedom were calculated using the Kenward-Roger method.

Table S2. Summary bolt and temperature data during tests of *Agrilus anxius* (bronze birch borer) in birch bolts, *Agrilus bilineatus* (twolined chestnut borer) in oak bolts, and *Agrilus sulcicollis* (European oak borer) in oak bolts when heated to various core temperatures for 30 continuous min, using constant chamber temperatures of 60 to 75°C. GLM results are given within *Agrilus* species. Means with the same letters are not significantly different ($P < 0.05$). Degrees of freedom were calculated using the Kenward-Roger method.

Table S3. Summary bolt and temperature data during tests of various borer (Cerambycidae and Curculionidae) survival in *Pinus resinosa* (red pine) bolts when heated to various core temperatures for 30 continuous min, using constant chamber temperatures of 60 to 75°C. GLM results are given within each core treatment. Means with the same letters are not significantly different ($P < 0.05$). Degrees of freedom were calculated using the Kenward-Roger method.

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