Kiln and microwave heat treatment of logs infested by the emerald ash borer (*Agrilus planipennis* Fairmaire) (Coleoptera: Buprestidae)

Pascal Nzokou✳
Sam Tourtellot
D. Pascal Kamdem✳

Abstract

Invasive alien pest species periodically infest forests in North America and worldwide, resulting in significant economic and ecological losses for areas involved. One common approach used to control pests is the establishment of quarantine zones, which impose limitations on circulation of products and therefore affect the economic viability of goods already affected by the infestation. This project investigated the use of kiln and microwave heat treatments for the sanitization of emerald ash borer infested logs. Four treatment temperatures of 50, 55, 60, and 65 °C were used; the logs were evaluated for insect emergence after appropriate time for insect maturation. Results showed that the kiln temperature of 65 °C was successful at sanitizing infested logs. This level is slightly above the Food and Agriculture Organization (FAO) level of 56 °C for 30 minutes recommended for pallets and wood packaging material. Microwave treatments were not as effective as kiln treatments, probably due to uneven distribution of the heat inside the microwave. Approaches to improve the microwave treatment are proposed.

Invasive alien insects and diseases are a continuous threat for trees and forest ecosystems due to international trade and involuntary movement and spread of vectors. Well-known examples of alien insect invasions include the chestnut blight disease, the Dutch elm disease, the gypsy moth, the Asian longhorn beetle, the Eurasian pine shoot beetle, and the hemlock woolly adelgid (Haack and Poland 2001, Fernandez 2003).

More recently, several areas in northeastern United States were infested with the emerald ash borer (EAB), *Agrilus planipennis* (Coleoptera: Buprestidae). This particular insect was first discovered in southeastern Michigan in the summer of 2002 (Poland and McCullough 2006). It is largely believed that infested crates, dunnage or pallets were the transportation mechanism that brought larvae or adult insects into the region (Haack et al. 2002). Since then the beetle has been identified throughout most of Michigan's Lower Peninsula, and in smaller occurrences in Ohio, Illinois, Indiana, Maryland, and southern Ontario, Canada. It is estimated that 25 million ash trees have been infected or killed in Michigan alone (roughly 2 percent of the state's 850 million ash trees) (Poland and McCullough 2006). In the United States as a whole, more than 8 billion ash trees, comprising 16 species and approximately 7.5 percent of the nation's hardwood volume, are at risk (Poland and McCullough 2006).

Similarly to other exotic insect infestations, the initial agency's response included imposing strict quarantine regulations

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The authors are, respectively, Assistant Professor, Lab. Assistant, and Professor, Dept. of Forestry, Michigan State Univ., East Lansing, Michigan (nzokoupa@msu.edu, tourtelot@msu.edu, Kamdem@msu.edu). This research project was funded by the USDA through the Southeast Michigan Resource and Development Council (SEMIRCD). The authors wish to acknowledge support from the Michigan Dept. of Natural Resources and the Dept. of Forestry at Michigan State Univ. This paper was received for publication in October 2007. Article No. 10415.

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on all articles or products capable of spreading the EAB. To date, most of the Lower Peninsula of Michigan is under quarantine, and new infestations areas have been discovered in the Upper Peninsula (Michigan Department of Agriculture 2006). The EAB has caused significant economic and environmental losses to private landowners and municipalities who are responsible to pay for the removal of infested trees on their properties. In addition to these direct losses, quarantine restrictions have also undoubtedly caused economic losses by preventing the movement of logs and certain types of valued wood products to their traditional markets.

We have been investigating approaches that could be used to sanitize logs and wood products, allowing their free circulation and marketing (Nzokou et al. 2006). Having more market opportunities for infested logs will provide additional revenue to non industrial private landowners, municipalities, and states and help alleviate some of the cost of tree removal programs in infested areas.

Several chemical treatments including borate (*disodium octoborate tetrahydrate*) and preventol TM (an imidacloprid formulation produced by Bayer Chemicals) were tested and proven effective at reducing insect emergence under laboratory conditions (Nzokou et al. 2006). However, concerns were raised over the environmental and health impact of wood products treated with chemicals, thus nonchemical approaches are being considered. The current project investigates the use of kiln and microwave heat treatments as sanitization methods for EAB infested logs. Both heat and microwave methods have been proven effective in other applications. For example, kiln treatment at 56 °C for 30 minutes is the recommended FAO standard (FAO 2002) for sanitizing wood packaging material.

The effectiveness of microwaves as a control of pathogens and pests in plants and soils has been known for a number of years (Baugh et al. 1998). In the food industry, where there has been considerable pressure to reduce the use of pesticides, microwave treatments have been used as an alternative for the eradication of insect pests with positive results (Shayesteh and Barthakur 1996, Tang et al. 2000, Phillips et al. 2001). Microwave technology was also used successfully in eradicating webbing clothes moths, *Tineola bisselliella* (Humm.), in textiles (Reagan 1982). In addition, a study of heat transfer in spruce wood conducted by Zielonka and Gierkik (1999) showed that microwaves developed peak temperatures at a layer 30 to 40 mm below the wood surface. The actual location of the feeding area of the Emerald Ash Borer is immediately below the bark in the phloem and outer secondary xylem, corresponding to the area of peak temperature for the microwave heating curve proposed by Zielonka and Gierkik (1999). Such characteristics make microwave treatment theoretically very well adapted to sanitizing ash logs against EAB.

The goal of this study was to investigate the use of kiln and microwave heat treatments for sanitization of logs infested by EAB. We also evaluated these treatments in relation to the posttreatment handling method by comparing indoors and outdoors rearing.

Materials and methods

Log preparation

Green logs were cut from infested ash trees harvested near Ann Arbor, Michigan. Before felling each tree, infestation by EAB was confirmed by removing small portions of the bark at breast height with a bark knife and looking for the presence of galleries and larvae. Only trees with evidence of recent infestation (having fresh galleries) were harvested for the study. Trees were harvested in February and March with insects still at their overwintering larval or prepupae stage about a centimeter inside the phloem. The main stem was divided into logs measuring approximately 0.9 m. Logs were assigned to the different treatments so that all treatments of the same type (heat or microwave) had logs coming from the same trees. The logs were then further divided into two halves; with one assigned to a treatment with logs reared indoors and the other to the exact same treatment with logs reared outdoors. The overall experimental design was a randomized complete blocks with 5 treatments replicated four times. Length and diameter were measured at three different points on each log, and the average of these three measurements used to compute the total bark surface area (**Table 1**). The average bark thickness was also measured and recorded (**Table 1**).

Treatments

Kiln heat treatments were applied using a 5.09 m^3 conventional laboratory kiln manufactured by Standard Dry Kiln Co., Indianapolis, Indiana. Preliminary trials were conducted to determine the dry and wet bulb settings needed to obtain a stable ambient kiln temperature of 82 °C (**Fig. 1**). Once the kiln temperature was stable, logs were inserted and monitored to the desired temperature and kept in for an additional 30 minutes before they were removed. Microwave treatments were conducted in a 2.8 GHz conventional inverter microwave (volume: 0.062 m^3, power: 1250 W) manufactured by Panasonic (Panasonic Co., Secaucus, New Jersey). Due to the limited volume of the microwave, two runs were necessary to treat logs assigned to each treatment temperature, and the treatment was stopped 30 minutes after the center thermocouple reached the treatment temperature.

For all treatments, two type K thermocouples wired to a datalogger were inserted to the center of the log and one centimeter into the phloem for continuous monitoring of temperature changes inside the log. For that purpose, a hole was drilled to the desired depth, the thermocouple was then inserted into the hole and the clear space around the wire filled with the powder removed from the drilling process. The hole was then sealed with silicone to avoid any temperature exchange between the hole and the ambient environment. The kiln air temperature was continuously measured using a third thermocouple placed inside for the kiln treatment. The ambient temperature was not monitored for the microwave treatment for safety reasons. Logs were removed 30 minutes after the temperatures of the core thermocouple reached levels of 50, 55, 60, or 65 °C. (**Fig. 1**) All treatments were applied on green logs with the initial MC between 40 percent and 70 percent.

Rearing

After treatment, logs were reared indoors and outdoors in structures constructed to allow for insect development to occur, while still trapping them and preventing them from escaping. Logs reared indoors were placed in thick walled cardboard tubes with plastic lids at both ends as described by Nzokou et al. (2006).

Logs reared outdoors were placed in individual wood enclosures covered with a mesh screen. Enclosures were placed

Table 1. — Average dimensions and bark area and thickness of logs used for each treatment.

Treatment		Length	Diameter	Bark area	Bark thickness
		-------------(mm)-------------		(m^2)	(mm)
Heat (kiln)	Control	453.7 (11.0)*	149.6 (7.8)	0.21 (0.012)	8.9 (1.9)
	HT50	464.3 (21.7)	142.0 (22.8)	0.20 (0.034)	8.0 (0.0)
	HT55	460.9 (13.0)	142.4 (14.2)	0.20 (0.022)	9.3 (1.8)
	HT60	455.4 (22.8)	144.4 (25.2)	0.20 (0.039)	8.9 (1.9)
	HT65	449.2 (28.2)	159.5 (19.0)	0.22 (0.039)	9.9 (2.3)
Microwave	Control	419.1 (41.8)	13.01 (50.1)	0.16 (0.047)	8.5 (2.3)
	MC50	457.2 (13.9)	9.68 (14.0)	0.14 (0.020)	8.0 (0.0)
	MC55	448.4 (59.5)	10.43 (19.0)	0.14 (0.018)	7.1 (0.9)
	MC60	456.4 (26.8)	10.04 (14.2)	0.14 (0.026)	7.1 (0.9)
	MC65	436.8 (19.8)	10.47 (27.4)	0.14 (0.034)	8.1 (2.6)

* Numbers in parentheses are standard deviations.

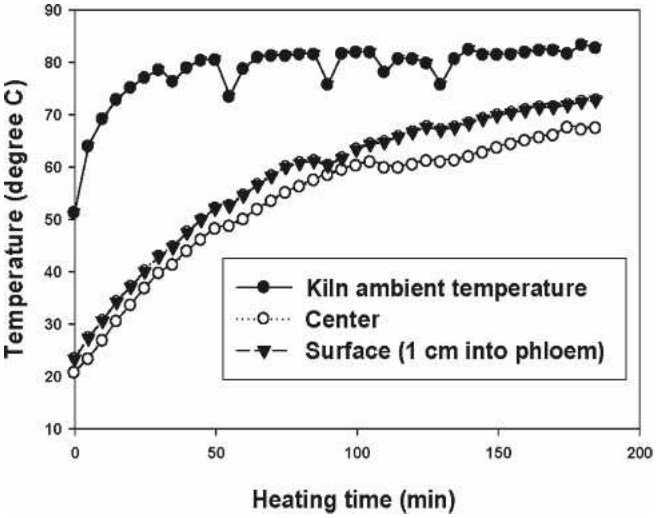

Figure 1. — Ambient and log temperatures during the kiln treatments. The small dips in ambient temperatures indicate the opening of the kiln for removal of logs for a given treatment. The removal decision was based on the center thermocouple.

outside at Michigan State University's Tree Research Center in East Lansing, Michigan, where they were fully exposed to rainfall, sunlight, and other weather events during the winter and following spring.

Data collection

For the indoors logs, rearing tubes were checked daily. Insects were collected in separate screw cups and labeled by emergence date and log identifier. Collected insects were fed ash leaves and cups were checked daily to measure the survival longevity of the insects under each treatment. After emergence had ceased, the rearing tubes were opened and the trapped EAB were collected and counted. A total count of emergent adults was calculated for each log by summing the number of EAB previously found in the cups to the number found in the tube. Tubes were then resealed and stored in an unheated storage area for the winter. They were reevaluated again in the summer of 2007 for further insect emergence.

The outdoors enclosures were checked for adult EAB weekly. Once emergence started, a weekly count was made to track the emergence progress. After emergence stopped, the enclosures were opened and the number of dead were counted and recorded. Enclosures were then resealed, and reevaluated in the spring and summer of 2007.

Data analysis

For each type of heat treatment, temperature level, and rearing scenario, the mean emergence density (MED) calculated as the mean number of emerged EAB adults per square meter of bark was computed. Due to large differences in variance, a Log10 transformation was applied to the data. The computer software, SAS version 9.1, was used to perform one-way ANOVA (PROC MIXED) tests. Kiln and microwave heat treatments, with logs reared both indoors and outdoors, were separately compared. If one or more of the means was found to differ from the rest at a multiple comparison adjusted significance level of 0.025, the Dunnett's procedure was used to determine which treatments were significantly different from their control using the same significance level. In order to compare the indoors-reared treatments to the outdoors-reared treatments, the mean difference between corresponding indoors and outdoors-reared logs was calculated for each treatment using the untransformed data. This value was then compared to an expected value of zero using a paired t-test at a significance level of 0.025.

Results and discussion

Emergence density

The average MED and standard errors for all treatments are summarized in **Table 2**. The data presented shows that kiln heat treatments were very effective in reducing insect emergence both for logs reared indoors and outdoors. For indoors-reared logs, the average MED of treated logs ranged from 0 to 1.8 adults per square meter compared to 58.7 adults per square meter for control logs. Both the lowest (50 °C) and highest (65 °C) temperature trials resulted in zero emergence. Similar trends were observed for logs reared outdoors with MED ranging from 0 to 1.2 adults per square meter for treated logs compared to 47.2 for control logs. Treatments at 50 °C, 60 °C, and 65 °C resulted in full control of the insect emergence and only the 55 °C treatment logs differed with a MED value of 1.2 adults per square meter. Treatments at the 50 °C temperature produced no insect emergence; however the next higher temperature tested of 55 °C failed to completely eradicate the insect in both the indoors and outdoors rearing methods. The reason why we obtained better control at 50 °C compared to 55 °C are not clear. However, we suspect that this could be due to uneven heat distribution in the 55 °C logs caused by variation in logs MC. The 65 °C treatment offered complete control for both indoors and outdoors rearing, indicating that it might be safer to go to this higher temperature to ensure killing of insect larvae from infected logs.

The one-way ANOVA tests (**Table 3**) showed that indoors and outdoors-reared conventional heat trials both produced a highly significant difference in MED ($p < 0.0001$ in both cases). The Dunnett's procedure showed that the MED for all

Table 2. — Mean emerald ash borer emergence densities (with standard error in parentheses) from logs treated with conventional and microwave heat and subsequently reared indoors and outdoors. Mean emergence densities that are significantly lower than their control at a significance level of 0.01 are marked with an asterisk (*).

Treatment	Treatment temperature	Mean emergence density (insects/m^2)	
		Kiln	Microwave
Indoor rearing	Control	58.7 (17.1)	36.3 (19.3)
	50 °C	0.0 (0.0)*	37.3 (9.2)
	55 °C	1.9 (1.8)*	21.9 (11.0)
	60 °C	1.0 (1.0)*	26.8 (15.1)
	65 °C	0.0 (0.0)*	1.4 (1.3)
Outdoor rearing	Control	47.2 (25.0)	64.7 (19.5)
	50 °C	0.0 (0.0)*	15.6 (8.8)
	55 °C	1.2 (1.2)*	10.0 (7.5)
	60 °C	0.0 (0.0)*	20.0 (13.8)
	65 °C	0.0 (0.0)*	20.7 (2.8)

temperature treatments were significantly lower than those of the control treatment in both indoors and outdoors rearing. Although we obtained full control for some treatments temperatures (50 °C, and 65 °C) more extensive testing should be done to determine the exact sufficient temperature requirements for treating EAB infested logs, despite the current FAO standard for treatment of packaging material is 56 °C for half an hour. It should be reminded the FAO standard is aimed at pallets and packaging materials and not logs as it was the case in the present study.

The microwave treatments surprisingly produced inconsistent reductions in MED. Indoors-rearing treatments resulted in average MED varying from 1.4 to 37.3 insects per square meter, compared to the control treatment MED of 36.3. When the logs were reared outdoors, average MED values ranged from 9.9 to 20.7, compared to a control treatment MED of 64.3. The statistical analysis showed that the microwave treatments did not significantly reduce the MED in both indoors (p = 0.132) and outdoors (p = 0.138) rearing. These results were surprising because similar temperature treatments were successful at controlling insect emergence using kiln heat treatments. We are hypothesizing that the ineffective sanitization with the microwave treatments could have been caused by the uneven distribution of the heating temperature inside the microwave during the treatment, because we observed that at the end of the treatments some sides of treated logs seemed to be warmer than others. Similar temperature distribution problems have been reported before (Zhao and Turner 2000). With the high costs of energy, and the level of energy needed to thoroughly heat logs to the desired 60 to 65 °C, microwave technology is still a very attractive solution for rapid heat sterilization of infested wood materials. However, the problem of ensuring appropriate temperature distribution needs to be addressed in the design and operation of the microwave.

There are several other ways to streamline the microwave heating process. Water greatly affects the dielectric properties of a substance (Zielonka and Gierlik 1999). Decreasing the MC of ash logs would allow microwaves to penetrate deeper into the wood. However, achieving a given MC for logs before treatment may be impossible and impractical in applications outside of the laboratory. Another avenue that may be used to improve microwave treatments involves radio wave frequency. It has been shown that for a given substance, dielectric properties are dependent upon the frequency of the microwaves used. These properties have been closely examined for the food and agriculture industries. Documented dielectric property curves have been developed that describe the function of wave frequencies in microwave sterilization for a number of foods and their common insect pests (Wang et al. 2003, Wang and Tang 2004, Nelson 2005). If these curves could be estimated for both ash wood and the EAB, it may be possible, with a known MC of the wood, to choose a frequency that increases the treatment efficiency and decreases the risk of damaging the wood by more accurately targeting the insects for heating.

The comparison between indoors and outdoors rearing methods (**Table 2**) shows no difference between the two methods for both heat and microwave treatments. This was confirmed by the statistical analysis that showed no significant difference between logs reared indoors and logs reared outdoors for either the conventional heat treatment (p = 0.29) or the microwave treatment (p = 0.46). These results indicate that the rearing method and posthandling conditions of the logs did not affect the efficacy of the treatments, suggesting that the most important factor in such treatment is the effective application and distribution of the appropriate temperature levels.

Survival longevity

Table 4 shows the mean number of days that the insects survived after emergence. The data presented is limited to treatments where adult insects emerged, were captured, and reared. The results show no difference in survival longevity between the various microwave treatments, indicating good potential for survival development and spread if for any reason the insect survived any of the heating temperatures tested. This result underscores the need to achieve full control to eliminate any chance of dispersal due to poor or uneven treatment.

All logs were reevaluated for further emergence in late spring and summer of 2007, and no adult emerged neither from any of the indoors or outdoors rearing treatments nor from control samples. This indicates that all insect development and emergence from the infested logs harvested for the current study occurred during the first year.

Conclusions

Emerald ash borer-infested logs were treated using two types of heat treatments (kiln and microwave) to identify nonchemical sanitization methods for EAB infested logs.

The kiln heat treatments produced highly significant reductions in the mean adult insect emergence density on logs reared both indoors and outdoors. However, although temperatures of 50, and 65 °C produced complete control of adult insect emergence, few adults emerged from some of the 55 °C and 60 °C treated logs preventing any claim of full control for all treatment temperatures used.

Microwave treatments did not provide significant reductions in insect emergence for all temperatures tested. We attributed the low effectiveness of microwave treatments to uneven heat distribution inside the microwave. As expected, no significant difference in treatment effectiveness was found between logs reared indoors and the logs reared outdoors for

Table 3. — Mixed model Anova results for MED of kiln and microwave treatments. Analysis was performed on the log10 transformed data set. Critical Dunnett's t values and Dunnett's minimum significant values are presented.

Source		Anova SS	Mean square	F value	P	Critical Dunnett's *t value*	Dunnett's minimum significant difference
Indoor rearing	Heat treatment	8.32	2.08	27.09	<0.0001	2.76	0.50
	Microwave	3.79	0.05	2.10	0.1320	2.76	1.30
Outdoor rearing	Heat treatment	7.01	1.76	26.26	<0.0001	2.78	0.50
	Microwave	3.68	0.92	2.05	0.1297	2.73	1.30

Table 4. — Survival longevity of adult emerald ash borers, in number of days, after emerging from logs heat treated using microwaves to eliminate infestation.

Treatment[a]	Temperature	Sample size	Mean survival period (no. of days)
Microwave	Control	10	13.7 (2.1)
	50°	12	12.8 (1.7)
	55°	8	17.1 (2.4)
	60°	11	14.8 (2.5)
	65°	0	---

[a] Kiln heat treatment not included because only a few adult insects emerged from these treatments.

either microwave heat treatments or kiln heat treatments; indicating that the posttreatment handling method will not have any influence on insect survival and emergence. Data of the survival longevity showed no apparent difference between temperature treatments, indicating that the insects will do well if they survived the treatment. This study suggests that the kiln heat treatment at a level of 65 °C or greater could be an effective sanitization process for EAB-infested logs and wood materials. Further studies using larger sample size are needed to determine the actual viability of the cutoffs temperature range and relation to the FAO standards on wood packaging materials.

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