Bark- and Wood-Borer Colonization of Logs and Lumber After Heat Treatment to ISPM 15 Specifications: The Role of Residual Bark

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ABSTRACT Wood packaging material (WPM) is a major pathway for international movement of bark- and wood-infesting insects. ISPM 15, the first international standard for treating WPM, was adopted in 2002 and first implemented in the United States in 2006. ISPM 15 allows bark to remain on WPM after treatment, raising concerns that insects could infest after treatment, especially if bark were present. We conducted field studies to evaluate insect infestation of green logs and lumber with varying amounts of bark after heat treatment. In a log study, Cerambycidae and Scolytinae (ambrosia beetles and bark beetles) readily infested and developed in logs with bark after heat treatment. In a lumber study, Cerambycidae and bark beetles laid eggs in all sizes of bark patches tested (≈25, 100, 250, and 1,000 cm^2) after heat treatment but did not infest control or heat-treated lumber without bark. Cerambycidae completed development only in boards with bark patches of 1,000 cm^2, whereas bark beetles completed development on patches of 100, 250, and 1,000 cm^2. Survival of bark beetles was greater in square patches (10 by 10 cm) versus rectangular patches (2.5 by 40 cm) of the same surface area (100 cm^2). In surveys at six U.S. ports in 2006, 9.4% of 5,945 ISPM 15-marked WPM items contained bark, and 1.2% of 563 ISPM 15-marked WPM items with bark contained live insects of quarantine significance under the bark. It was not possible to determine whether the presence of live insects represented treatment failure or infestation after treatment.

KEY WORDS Cerambycidae, Curculionidae, Scolytidae, Scolytinae, heat treatment

Wood packaging material (WPM; e.g., pallets and crating) associated with international trade is an important pathway by which bark- and wood-boring insects can be transported among countries (Haack 2001, Allen and Humble 2002, McCullough et al. 2006, Kenis et al. 2007, Zahid et al. 2008, Colunga-Garcia et al. 2009, Roques et al. 2009). In recent decades, several species of borers have become established beyond their native range throughout the world, with WPM often implicated as the means of their conveyance (Haack 2006, Brockerhoff et al. 2006, Evans 2007, Langor et al. 2009). In the past century, WPM commonly was manufactured from untreated, low-grade green lumber, often with residual bark. As a result, such WPM was likely to harbor bark- and wood-boring pests (Allen and Humble 2002, Evans 2007).

In recognition of the threat posed by untreated WPM, an international standard entitled "Guidelines for regulating wood packaging material in international trade" was adopted in 2002 and designated as International Standards for Phytosanitary Measures No. 15 or ISPM 15 (FAO 2002, Keiran and Allen 2004, Evans 2007). Heat treatment and fumigation with methyl bromide are the two currently approved treatments for WPM manufactured from raw wood (FAO 2002). International Standards for Phytosanitary Measures are adopted by the Commission on Phytosanitary Measures, the governing body of the International Plant Protection Convention (IPPC). The IPPC is an international treaty that was adopted in 1951, revised in 1997, and is administrated within the Food and Agriculture Organization of the United Nations. As of March 2009, there were 170 countries or multicountry contracting parties to the IPPC. The Commission on Phytosanitary Measures develops and adopts International Standards for Phytosanitary Measures through a process that includes consultation with member countries. New WPM treatments will be evaluated and possibly added to future revisions of ISPM 15.

ISPM 15 treatments are aimed at killing pest organisms that reside in the wood at the time of treatment. However, the current version of ISPM 15 does not require elimination of bark, so concerns have been raised that insects could infest WPM after treatment, especially when bark is present given that many borers require bark for successful oviposition (Evans 2007). The International Forestry Quarantine Research Group (IFQRG; http://www.forestry-quarantine.org) was formed in 2003 and consists primarily of regulators, researchers, and WPM industry representatives (Keiran and Allen 2004). The first two research questions discussed by IFQRG were related to ISPM

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15: 1) Will insects infest green barked logs and lumber with varying amounts of residual bark after treatment to ISPM 15 standards? and 2) What percentage of ISPM 15-marked WPM used in international trade contains live bark- and wood-infesting insects? In this paper, we discuss U.S. studies that address these questions.

Materials and Methods

2004–2005 Log Study. On 14 June 2004, we cut 48 logs (1 m in length, 16–22 cm in diameter) from the trunks of six red pine (*Pinus resinosa* Ait.), two red maple (*Acer rubrum* L.), two northern red oak (*Quercus rubra* L.), and three pignut hickory [*Carya glabra* (Miller) Sweet.] trees at Michigan State University's (MSU) Kellogg Experimental Forest near Augusta, Kalamazoo County, MI (42.3° N, −85.4° W). All trees seemed healthy and had no signs or symptoms of borer infestation along the trunk. These species were selected because they are commonly used in Michigan to manufacture WPM. Logs were transported to the Forestry Department at MSU in East Lansing, Ingham County, MI (42.7° N, −84.5° W), where they were stored indoors at room temperature (20–24°C). We did not remove bark from the experimental logs based on the rationale that if insects failed to colonize heat-treated logs with full bark intact, there would be little likelihood of colonization when lesser amounts of bark remained.

On 15–16 June, half of the logs were heat-treated in a kiln at MSU according to ISPM 15 specifications (minimum 56°C core temperature for 30 min; FAO 2002). Logs of similar diameter and species were treated together in the kiln so that heating times were similar. We used thermocouple probes (A93601-26, Cole Parmer, Vernon Hills, IL) to monitor inside-kiln air temperature and core temperatures of three selected logs. All temperatures were monitored in real time using Cole Parmer dataloggers (K-3801 0-16) and software (K-38010-50).

On 17 June, all logs were placed along the edge of a power-line corridor that was cut through a mature natural stand of conifers and hardwoods at MSU's Kellogg Experimental Forest. We selected this location because stand thinning had occurred along the corridor during each of the previous few years. Thus, numerous bark- and wood-infesting insects were expected. The experimental logs were laid horizontally and elevated a few centimeters off the ground using pieces of aged lumber to facilitate insect infestation on all log surfaces. Treated and control logs were intermingled.

On 21 July after 34 d exposure in the field, 24 of the 48 logs (three logs for each tree species x treatment combination) were taken from the field to our laboratory at MSU. Logs were cut in half with one portion placed individually in a rearing tube and maintained indoors at room temperature; the other portion was stored in a walk-in cold room (≈4°C) until dissection. The rearing tubes were inspected one to two times weekly through December 2004, with all insects collected, counted, and identified. For the logs that were immediately dissected, we first recorded log length, diameter, and number and kinds of exit holes present. Exit holes were matched to the galleries beneath the bark to aid in borer identification. After debarking, we then recorded the number and kinds of borers present, life stages present, and occurrence and number of borer galleries. If galleries entered the sapwood, they were opened with chisel and hammer. After rearing, logs were measured, dissected, and the number and kinds of borer galleries present recorded as above. Initial attack density was calculated for each log by dividing the number of ambrosia beetle entrance holes on the sapwood surface, the number of bark beetle gallery systems, and the number of cerambycid larval galleries by the log surface area.

On 7 February 2005, the remaining 24 logs were taken from the field to our laboratory and treated as described previously. Insects were reared from a portion of each log through 7 July 2005. Emergence density was calculated for each log by dividing the number of reared adult ambrosia beetles, bark beetles, and cerambycids by the log surface area.

2005–2006 Board Study. On 21 June 2005, we cut 28 logs (2 m in length) from the trunks of six healthy red pine trees (17–21 cm diameter at breast height) on the Huron-Manistee National Forest near White Cloud, Newaygo County, MI (43.5° N, −85.7° W). The logs were transported to the Forestry Department at MSU and stored indoors at room temperature. Over the next week, we prepared 192 1-m-long boards by using a portable sawmill. Half of the boards were ≈2.5 cm (≈1 in.) in thickness, and half were ≈10 cm (≈4 in.) in thickness. Varying amounts of bark were retained along one edge of each board. There were four bark classes: 1) "bark free" in which all bark was removed, 2) "small patches" in which eight bark patches (25 cm^2 each) were retained, 3) "large patches" in which two bark patches (100 cm^2 each) were retained, and 4) "all bark" in which all bark was retained along one edge. The shape of the small (25 cm^2) bark patches was rectangular on both the 2.5- and 10-cm-thick boards and measured ≈2.5 by 10 cm. The shape of the large bark patch (100 cm^2) was rectangular on the 2.5-cm-thick boards (measuring ≈2.5 by 40 cm) but square on the 10-cm-thick boards (measuring ≈10 by 10 cm). The area of bark retained on the "all bark" boards was ≈250 cm^2 on the 2.5-cm-thick boards (2.5 by 100 cm) and 1,000 cm^2 on the 10-cm-thick boards (10 by 100 cm). We used 12 replicates for each of the 16 bark × treatment × board thickness combinations (192 boards).

Half of the boards were heat-treated (minimum 56°C core temperature for 30 min) and half served as untreated controls. The 2.5-cm-thick boards were heated separately from the 10-cm-thick boards. Kiln and board temperatures were monitored with thermocouple probes and dataloggers as described for the 2004 log study.

All boards were placed in a red pine stand on 30 June 2005 at MSU's Kellogg Experimental Forest. Thinning had occurred in this pine stand the previous winter so high borer populations were expected. The various categories of boards were divided equally into six piles and then stacked randomly in a crisscross manner on the forest floor—two boards of similar treatment per row with the barked edge of each board facing outward. The first pair of boards was elevated above the ground as described in the log study. On 23 July, all boards were returned to the laboratory where half were placed in cold storage until dissected and assessed for insect colonization. The others were placed in individual cardboard tubes to rear insects until 31 October 2005. Beginning on 31 October, three of the six boards from each treatment combination were subjected to a 95-d cold period ($\approx$4°C) and then placed in rearing tubes from 3 February to 26 April 2006. This cold period was provided for those insects that might require an overwintering period before completing development and emerging as adults. All boards were dissected and data on the presence of borers and their galleries recorded.

2006 Port Survey. A survey was conducted at six U.S. ports during the summer of 2006 to evaluate the incidence of bark and live insects on ISPM 15-marked WPM associated with imported goods. The port surveys were conducted in cooperation with Customs and Border Protection agricultural officers of the U.S. Department of Homeland Security. The surveys were conducted for 2 wk each at the ports of Detroit, MI; Elizabeth, NJ; Laredo, TX; Long Beach, CA; Savannah, GA; and Seattle, WA. Only WPM with the ISPM 15 mark was examined. Two general surveys were conducted in accordance with a study design developed by the Forestry Panel of the North American Plant Protection Organization. The first focused on the incidence of bark on marked WPM and the size of individual bark patches. The second focused on the incidence of live insects under individual patches of bark on marked WPM. In most cases, WPM items inspected for live insects in the second survey consisted of WPM items that contained bark during the first survey. On days when there were numerous WPM items, the items inspected for each of the two surveys represented two distinct subsets of all of the WPM available.

In the first survey, we inspected five types of WPM: blocks, crating, dunnage, pallets, and spools. We considered a single WPM item to consist of one entire pallet, all the crating associated with a single product, or a single block, spool, or piece of dunnage. We inspected each item for bark on all visible external surfaces. A forklift often was used to lift pallets to facilitate inspection. WPM items such as pallets and spools were not disassembled, so some bark might have been overlooked on the interior boards. Complete inspection of all surfaces was possible only with blocks and dunnage. The largest bark patch on each individual WPM item was assigned to one of four size classes: 1) no bark found, 2) smaller than a credit card ($\approx$45 cm^2), 3) larger than a credit card but smaller than a standard sheet of typing paper ($\approx$600 cm^2), and 4) larger than a sheet of paper. These two bark patch sizes were discussed by IPPC's Expert Working Group on Debarking of Wood and Bark Freedom in 2005 in terms of pest risk as well as ease of implementation worldwide for setting tolerance limits for bark on WPM (IPPC 2005). For each WPM item inspected, we recorded the type of WPM item (e.g., crating, dunnage, pallet), approximate size of the largest bark patch encountered, all information on the ISPM 15 mark (country of origin, manufacturer, and type of treatment), and type of product (e.g., granite, steel, tile) associated with the WPM.

In the second survey, we used knives and chisels to remove and inspect individual bark patches for insects of quarantine significance. We excavated all galleries that entered the sapwood to recover insects that might be present. We recorded the type of WPM item inspected, dimensions of each individual board with bark, number of bark patches present, approximate dimensions of each bark patch, presence of insects and whether they were alive or dead, identity of insects found, all information on the ISPM 15 mark, and associated imported products. We also used a wood-moisture meter (J-lite, Delmhorst Instrument Company, Towaco, NJ) to estimate the wood moisture level (dry-weight basis) near the approximate center of each bark patch.

Statistical Analyses. For the 2004–2005 log study and the 2005–2006 board study, density values for parent-adult scolytine gallery systems, cerambycid larval galleries, and emerged adults (based on rearing data) were calculated on the basis of the total bark surface area for each log or board. Values for mean density were transformed ($\log_{10} + 1$) to improve normality. Mean density values for logs and boards were compared between heat-treatment and controls by one-way analysis of variance (ANOVA) (PROC GLM) (SAS Institute 2001). If the ANOVA was significant at the $\alpha = 0.05$ level, a Student–Newman–Keuls multiple range test was used to separate the means. Similarly, the relationship between the wood-moisture level beneath the bark patch and the surface area of the patch was analyzed with linear regression (PROC GLM).

Results

2004–05 Log Study. Several species of bark- and wood-boring beetles (Coleoptera: Cerambycidae and Curculionidae: Scolytinae) colonized and successfully reproduced in both heat-treated and untreated logs of all tree species tested (Table 1). It should be noted that although current taxonomy recognizes Scolytinae as a subfamily within Curculionidae (Arnett et al. 2002), most agencies involved in pest interceptions worldwide, as well as the language in ISPM 15 itself, recognize Scolytidae as a distinct beetle family (FAO 2002, Haack 2006). Mean attack densities of the scolytines known as ambrosia beetles (we reared species of *Gnathotrichus, Monarthrum, Xyleborinus, Xylosandrus,* and *Xyloterinus*) were significantly higher on heat-treated logs than on control logs for hickory, oak, and pine, but similar for maple (Table 2). The scolytines known as true bark beetles (we reared species of *Hylastes, Ips, Orthotomicus,* and *Polygraphus*) were

Table 1. Species and number of adult Cerambycidae (CER) and adult Scolytinae (SCO) collected during the 2004–2005 logs study and the 2005–2006 lumber study by tree species and wood treatment

Tree species family: insect species[a]	No. collected by study	
	Heat-treated	Control
Acer rubrum 2004–2005 log study		
CER: *Urographis fasciatus* (DeGeer)	21	4
SCO: *Gnathotrichus materiarius* (Fitch)	1	2
SCO: *Monarthrum mali* (Fitch)	191	1
SCO: *Xylosandrus germanus* (Blandford)	35	4
Carya glabra 2004–2005 log study		
CER: *Saperda discoidea* F.	0	1
CER: *Urographus fasciatus* (DeGeer)	16	0
CER: *Xylotrechus colonus* (F.)	14	3
SCO: *Monarthrum fasciatum* (Say)	8	0
SCO: *Monarthrum mali* (Fitch)	72	2
SCO: *Xyleborinus saxeseni* (Ratzeburg)	1	0
SCO: *Xylosandrus germanus* (Blandford)	349	0
Quercus rubra 2004–2005 log study		
CER: *Urographus fasciatus* (DeGeer)	4	19
SCO: *Gnathotrichus materiarius* (Fitch)	2	0
SCO: *Monarthrum fasciatum* (Say)	1	0
SCO: *Monarthrum mali* (Fitch)	35	19
SCO: *Xylosandrus germanus* (Blandford)	18	0
Pinus resinosa 2004–2005 log study		
CER: *Acanthocinus obsoletus* (Oliver)	3	25
CER: *Monochamus notatus* (Drury)	0	4
SCO: *Gnathotrichus materiarius* (Fitch)	715	91
SCO: *Ips grandicollis* (Eichhoff)	16	233
SCO: *Monarthrum fasciatum* (Say)	4	0
SCO: *Monarthrum mali* (Fitch)	5	1
SCO: *Orthotomicus caelatus* (Eichhoff)	1,695	207
SCO: *Polygraphus rufipennis* (Kirby)	3	1
SCO: *Xyleborinus saxeseni* (Ratzeburg)	1	0
SCO: *Xylosandrus germanus* (Blandford)	6	0
Pinus resinosa 2005–2006 lumber study		
CER: *Monochamus notatus* (Drury)	2	1
SCO: *Dryocoetes autographus* (Ratzeburg)	2	1
SCO: *Gnathotrichus materiarus* (Fitch)	3	0
SCO: *Hylastes opacus* Erichson	274	119
SCO: *Ips grandicollis* (Eichhoff)	311	529
SCO: *Orthotomicus caelatus* (Eichhoff)	49	2
SCO: *Xylosandrus germanus* (Blandford)	6	1

In the 2004–2005 log study, there were six logs per tree species per treatment. Half of the logs were removed after 34 d in the field during June–July 2004. The others were removed from the field in February 2005 after exposure to winter temperatures. In the 2005–2006 lumber study, there were 96 boards per treatment, which each included boards of two thicknesses and four bark classes.

[a] Members of the scolytine genera *Dryocoetes, Hylastes, Ips, Orthotomicus,* and *Polygraphus* are true bark beetles; members of the genera *Gnathotrichus, Monarthrum, Xyleborinus, Xylosandrus,* and *Xyloterinus* are ambrosia beetles.

found only on pine logs. When data for all bark beetle species were pooled, mean attack densities (based on gallery systems) were significantly higher on heat-treated logs than on control logs (Table 2). However, when analyzed by individual bark beetle species, mean *Orthotomicus caelatus* (Eichhoff) attack density was highest on heat-treated logs, whereas mean *Ips grandicollis* (Eichhoff) attack density was highest on control logs (Table 2). Mean densities of cerambycid larvae (we reared species of *Acanthocinus, Monochamus, Saperda, Urographis,* and *Xylotrechus*) did not vary significantly between heat-treated and control logs for any of the four tree species tested (Table 2).

The general pattern of mean emergence densities among adult scolytines (for logs not exposed to winter conditions; Table 3) and cerambycids (for logs exposed to winter conditions; Table 3) were broadly similar to the original patterns of attack densities (Table 2). For example, mean emergence densities for ambrosia beetles and *O. caelatus* were highest on heat-treated logs, highest for *I. grandicollis* on control logs, and similar between treatments for cerambycid (Table 3). Most cerambycids apparently required exposure to cold before completing development, because only *Acanthocinus obsoletus* (Oliver) emerged from logs without first experiencing a cold period.

2005–2006 Board Study. Bark beetles and cerambycids infested all sizes of bark patches on both heat-treated and control boards but did not infest boards without bark or the bark-free areas on boards with bark patches (Table 4). Four species of bark beetles and one species of cerambycid were collected from the pine boards (Table 1). Although bark beetle and cerambycid eggs were laid in the smallest bark patches (25 cm^2) on boards of both thicknesses, complete development did not occur for any borer species on the 25-cm^2 patches. However, complete development of bark beetles did occur on large bark patches (100 cm^2), but only on 10-cm-thick boards where bark patches were square (Table 4). Although bark beetles and cerambycids readily colonized the 2.5-cm-thick boards that retained all bark along one face, complete development occurred only rarely for bark beetles (one of 12 boards) and not at all for cerambycids (Table 4). By contrast, on 10-cm-thick boards where all bark was retained along one face, bark beetles completed development on all boards, whereas cerambycids completed development on six of 12 boards (Table 4).

Mean densities of bark beetle gallery systems, cerambycid larval galleries, and emerged adults for both bark beetles and cerambycids generally were similar between the heat-treated and control boards of similar thickness and bark patch size (surface area) (Table 4). The percentage of boards colonized by bark beetles and cerambycids tended to decrease with decreasing patch size for boards of similar thickness and treatment (Table 4).

We found 51 ambrosia beetle entrance holes on the boards, including one on a 2.5-cm-thick board and 50 on the 10-cm-thick boards (data not shown). In all but one case, adult ambrosia beetles entered the wood through the sapwood surface where bark had been removed. In one case, attack was initiated through the bark of a 10-cm-thick heat-treated board with all bark retained. Forty-eight entrance holes were on control boards and three were on heat-treated boards. Although several ambrosia beetle galleries were initiated, apparently all had been abandoned given that none extended deeper than 2 cm. Also, at the time of dissection, there were no parent adults, eggs, or larvae. All of the adult ambrosia beetles collected from boards held in the rearing tubes likely were parent adults because they were collected within 9 d after the boards were placed in the rearing tubes.

Table 2. Mean ± SEM attack density of ambrosia beetles, bark beetles, and cerambycid larvae on four species of recently cut barked logs that were subjected to natural infestation after treatment (heat treatment or untreated controls) in Michigan in 2004

Tree[a]	Insect[b]	Mean attack density (no./m^2 of bark)			
		Heat	Control	*F*	*P*
C. glabra	Ambrosia beetles	442.5 ± 49.8	4.7 ± 3.2	79.7	0.0001
	Cerambycidae	72.6 ± 13.0	211.6 ± 65.6	3.2	0.1052
A. rubrum	Ambrosia beetles	114.0 ± 22.1	61.4 ± 9.8	3.1	0.1078
	Cerambycidae	31.6 ± 17.9	78.8 ± 43.1	0.03	0.8588
Q. rubra	Ambrosia beetles	124.5 ± 16.9	56.3 ± 18.6	5.3	0.0448
	Cerambycidae	25.0 ± 15.6	117.8 ± 53.4	0.7	0.4146
P. resinosa	Ambrosia beetles	168.2 ± 34.2	4.0 ± 1.6	55.1	0.0001
	Bark beetles	118.1 ± 14.9	69.2 ± 11.2	7.3	0.0224
	I. grandicollis	7.3 ± 3.0	43.1 ± 5.0	21.7	0.0009
	O. caelatus	110.2 ± 13.7	26.0 ± 12.6	10.4	0.0091
	Cerambycidae	9.7 ± 8.2	14.4 ± 8.2	0.3	0.5760

[a] Half of the logs were dissected in late summer 2004, and the other half were dissected in spring 2005 after experiencing winter conditions. $N = 6$ logs per tree species per treatment. For each comparison (within rows), df = 1, 10.
[b] Principal species of bark- and wood-infesting insects and sample sizes are listed in Table 1.

2006 Port Survey. In the first survey, bark was found on 560 (9.4%) of the 5,945 WPM items inspected for bark at six U.S. ports (Table 5). The 5,945 WPM items originated from 50 countries, the 10 most frequent of which were Italy (1,399 WPM items inspected), United Kingdom (1,160), Brazil (682), Turkey (369), China (310), Germany (260), Mexico (249), Spain (224), Russia (204), and Sweden (123). Approximately 68% of the 5,945 WPM items had been heat-treated, whereas 32% had been fumigated (Table 5). Apart from the single spool that was inspected, the occurrence of bark was broadly similar on blocks, crating, dunnage, and pallets, ranging from 7% of the dunnage to 17% of the crating (Table 5). Of the 560 WPM items with bark, 317 (56.6%) had bark patches that were all smaller than a credit card (45 cm^2), 232 items (41.4%) had at least one bark patch larger than a credit card but smaller than a sheet of paper (600 cm^2), and 11 items (2.0%) had at least one bark patch larger than a sheet of paper (Table 5). Individual patches of bark in each of the three size classes used in this survey were found on each of the four types of WPM items where bark was present.

In the second survey, 564 marked WPM items with bark were inspected for live insects. These items originated from 26 countries; the top 10 were Italy (143 WPM items), Mexico (97), Turkey (83), United Kingdom (38), Brazil (37), China (34), Spain (30), Viet-

Table 3. Mean ± SEM emergence density of adult ambrosia beetles, bark beetles, and cerambycids on four species of green barked logs that were heat-treated and then subjected to natural infestation in Michigan during 2004 and 2005

Tree[a]	Insect[b]	Mean emergence density (no./m^2 of bark)			
		Heat	Control	*F*	*P*
		Logs in field June–July 2004 (not exposed to winter conditions)			
C. glabra	Ambrosia beetles	543.3 ± 128.0	2.4 ± 2.4	55.3	0.0017
A. rubrum	Ambrosia beetles	112.2 ± 18.1	16.4 ± 8.9	13.1	0.0223
Q. rubra	Ambrosia beetles	63.9 ± 6.8	21.9 ± 7.4	8.2	0.0455
P. resinosa	Ambrosia beetles	268.9 ± 91.2	17.0 ± 15.2	8.8	0.0416
	Bark beetles	1,352.0 ± 639	429.8 ± 98.6	4.0	0.1163
	I. grandicollis	20.0 ± 20.0	278.7 ± 26.4	9.6	0.0363
	O. caelatus	1,328.3 ± 615.5	151.1 ± 72.5	12.2	0.0252
	Cerambycidae	2.4 ± 2.4	14.7 ± 7.4	1.2	0.3291
		Logs in field June 2004 to Feb. 2005 (exposed to winter conditions)			
C. glabra	Ambrosia beetles	350.1 ± 168.4	0 ± 0	98.6	0.0006
	Cerambycidae	36.1 ± 28.6	3.6 ± 0.3	3.1	0.1526
A. rubrum	Ambrosia beetles	493.9 ± 276.0	2.1 ± 2.1	36.6	0.0038
	Cerambycidae	27.0 ± 21.1	4.3 ± 4.3	0.9	0.4072
Q. rubra	Ambrosia beetles	9.0 ± 9.0	0 ± 0	1.0	0.3739
	Cerambycidae	3.9 ± 1.9	23.3 ± 5.3	7.3	0.0540
P. resinosa	Ambrosia beetles	421.5 ± 223	80.2 ± 59.8	2.8	0.1671
	Bark beetles	459.8 ± 192	85.6 ± 75.4	1.0	0.1627
	I. grandicollis	0 ± 0	2.4 ± 2.4	1.0	0.3739
	O. caelatus	456.2 ± 191	81.8 ± 73.6	3.1	0.1523
	Cerambycidae	1.2 ± 1.2	13.9 ± 8.4	1.7	0.2633

[a] One set of logs ($N = 3$ logs per treatment per tree species) was subjected to natural infestation during June to July 2004 and then stored indoors in rearing tubes through December 2004, whereas a second set of logs ($N = 3$ logs per treatment per tree species) was subjected to natural infestation from June 2004 to February 2005 and then stored indoors through July 2005. For each comparison (within rows), df = 1, 4.
[b] Principal species of bark- and wood-infesting insects are listed in Table 1.

Table 4. Mean ± SEM bark beetle and cerambycid gallery and exit hole densities per square meter of bark surface area and percentage of boards with evidence of insect colonization on recently cut 2.5-cm-thick and 10-cm-thick red pine boards with varying amounts of residual bark that were heat-treated or left as untreated controls and exposed to natural infestation during summer 2005 in Michigan before taken to the laboratory for rearing and dissection

Bark patch size	2.5-cm-thick lumber			10-cm-thick lumber		
	Heat	Control	*P*	Heat	Control	*P*
	Bark beetle gallery density (% of boards with bark beetle galleries)[a,b]					
All bark	107.3 ± 42.7 (67%)	88.0 ± 26.5 (67%)	0.99	169.1 ± 37.5 (100%)	91.7 ± 7.0 (100%)	0.05
Large patch	72.7 ± 35.3 (55%)	41.7 ± 10.4 (67%)	0.82	141.7 ± 31.9 (83%)	125.0 ± 31.7 (83%)	0.86
Small patch	45.5 ± 20.7 (45%)	83.3 ± 21.6 (83%)	0.07	125.0 ± 36.1 (75%)	83.3 ± 34.5 (50%)	0.24
Bark free	0 ± 0 (0%)	0 ± 0 (0%)		0 ± 0 (0%)	0 ± 0 (0%)	
	Bark beetle exit-hole density (% of boards with bark beetle exit holes)[a,c]					
All bark	56.6 ± 56.6 (17%)	0 ± 0 (0%)	0.34	191.3 ± 39.8 (100%)	249.5 ± 46.2 (100%)	0.36
Large patch	0 ± 0 (0%)	0 ± 0 (0%)		175.0 ± 87.3 (50%)	141.7 ± 70.0 (50%)	0.77
Small patch	0 ± 0 (0%)	0 ± 0 (0%)		0 ± 0 (0%)	0 ± 0 (0%)	
Bark free	0 ± 0 (0%)	0 ± 0 (0%)		0 ± 0 (0%)	0 ± 0 (0%)	
	Cerambycid gallery density (% of boards with cerambycids galleries)[a,b]					
All bark	115.6 ± 36.3 (75%)	110.3 ± 37.5 (83%)	0.88	83.6 ± 14.8 (92%)	129.0 ± 13.4 (100%)	0.06
Large patch	163.6 ± 51.8 (73%)	116.7 ± 39.1 (58%)	0.50	241.7 ± 61.5 (75%)	270.8 ± 73.7 (92%)	0.47
Small patch	168.2 ± 62.6 (64%)	100.0 ± 31.4 (58%)	0.75	241.7 ± 73.8 (67%)	395.8 ± 111.0 (75%)	0.54
Bark free	0 ± 0 (0%)	0 ± 0 (0%)		0 ± 0 (0%)	0 ± 0 (0%)	
	Cerambycid exit-hole density (% of boards with cerambycid exit holes)[a,c]					
All bark	0 ± 0 (0%)	0 ± 0 (0%)		4.9 ± 2.5 (66%)	2.4 ± 2.4 (33%)	0.51
Large patch	0 ± 0 (0%)	0 ± 0 (0%)		0 ± 0 (0%)	0 ± 0 (0%)	
Small patch	0 ± 0 (0%)	0 ± 0 (0%)		0 ± 0 (0%)	0 ± 0 (0%)	
Bark free	0 ± 0 (0%)	0 ± 0 (0%)		0 ± 0 (0%)	0 ± 0 (0%)	

[a] Species of bark- and wood-infesting insects reared from boards are listed in Table 1.
[b] Mean gallery density values were based on sample sizes of 11–12 boards. For each comparison (within rows of similar board thickness), df = 1, 21 or 1, 22.
[c] Mean exit-hole density values were based on sample sizes of five to six boards. For each comparison (within rows of similar board thickness), df = 1, 9 or 1, 10.

nam (21), India (18), and Canada (11). There were 699 bark patches on the 564 WPM items: 489 WPM items had one bark patch, 52 had two, 10 had three, three had four, four had five, two had seven, one had nine, and two had 10. The individual patches of bark ranged in size from 0.3 to 710 cm^2 (Table 6).

Wood-moisture level measured beneath the bark patches ($N = 699$) ranged from 6 to 30% (dry-weight basis) and averaged 15.9% (Table 6). Mean wood-moisture content beneath the bark patches was broadly similar among different types of wood packaging, with average values ranging from 13.5 to 17.5% (Table 6). There was no significant linear relation between wood-moisture level beneath the bark patch and surface area of the bark patch ($F = 2.56$; df = 1,697; $P = 0.11$). The mean ± SEM wood-moisture level, measured beneath the seven bark patches that harbored live borers, was 17.4 ± 1.3% with a range of 14–25%.

Live insects of quarantine significance were found beneath seven bark patches on seven distinct WPM items (1.2% of 564 WPM items, 1.0% of 699 bark patches); two WPM items contained bostrichids, one had cerambycids, and four had scolytines (Table 7). The ISPM 15 mark on six of the seven WPM items with live borers signified heat treatment, whereas the other item indicated fumigation. The seven WPM items with live borers were detected at two ports (Long Beach, CA and Savannah, GA); all had originated in Turkey and were associated with tiles. The bostrichids were *Stephanopachys* spp., the cerambycid larvae were not identified beyond family, and all adult scolytines were

Table 5. Number of WPM items inspected, size of the largest bark patch present on each WPM item, percentage of WPM items with bark, and type of ISPM 15 treatment applied to various types of WPM inspected at six U.S. ports in 2006

WPM type	Total	Size of largest bark patch[a] (no.)				% with bark	Treatment (no.)[b]	
		None	0 < 45 cm^2	45 > 600 cm^2	>600 cm^2		HT	MB
Blocks	47	40	1	5	1	14.9	29	18
Crating	979	815	104	56	4	16.8	709	270
Dunnage	3,465	3,238	131	92	4	6.6	2,152	1,313
Pallets	1,453	1,291	81	79	2	11.1	1,173	280
Spool	1	1	0	0	0	0	1	0
Total	5,945	5,385	317	232	11	9.4	4,064	1,881

[a] Size of largest bark patch found on each WPM item was assigned to one of four size classes: 1, no bark found; 2, smaller than a credit card (≈45 cm^2); 3, larger than a credit card but smaller than a standard sheet of paper (≈600 cm^2); and 4, larger than a sheet of paper.
[b] ISPM 15 treatments: HT, heat treatment; MB, methyl bromide fumigation.

Table 6. Summary data for mean ± SEM size and wood moisture content of individual bark patches found on 564 WPM items inspected at six U.S. ports in 2006, by type of WPM

WPM type	No. patches	Bark patch size (cm^2)		Wood moisture content (%)	
		Mean ± SEM	Range	Mean ± SEM	Range
Blocks	4	84.0 ± 25.0	32.5–148.0	13.5 ± 1.5	9–15
Crating	195	48.7 ± 5.1	0.3–522.0	15.4 ± 0.4	6–30
Dunnage	291	66.0 ± 5.7	3.0–670.0	17.5 ± 0.4	6–30
Pallets	209	65.0 ± 6.1	3.0–710.0	14.0 ± 0.4	6–30
Spool	0				
Total	699	60.9 ± 3.3	0.3–710.0	15.9 ± 0.2	6–30

Wood moisture content was recorded soon after bark removal near the approximate center of the bark patch.

Orthotomicus erosus (Wollaston). Adult *O. erosus* were present under two bark patches with live scolytines; only larvae were present in the other two patches. All individuals in the four patches with live scolytines likely were *O. erosus* because all were on WPM that originated from the same country, were in the same shipping container and associated with the same product, and were stamped with the same ISPM 15 mark, signifying that they were manufactured at the same facility. Moreover, characteristics of the gallery systems (e.g., length and width) were similar for the four patches with live scolytines, further suggesting they were the same species of bark beetle. It is interesting to note that during 1985–2000, there were 97 interceptions of borers on WPM from Turkey at U.S. ports, of which *Stephanopachys* and *Orthotomicus* were the most commonly intercepted bostrichid and scolytine genera, respectively. Similarly, the three most commonly intercepted cerambycid genera from Turkey were *Monochamus*, *Asemum*, and *Stromatium*, listed in decreasing order of interception frequency (Haack 2006, supplemental data).

Six of the seven bark patches with live borers were associated with crating; one was associated with a pallet (Table 7). Bostrichids were present under bark patches that measured 24 and 36 cm^2. The cerambycid was under a 120-cm^2 bark patch. The scolytines were under bark patches of 16, 45, 261, and 522 cm^2. Five of the seven patches (16, 24, 36, 120, and 261 cm^2) with live borers had only partial galleries (i.e., truncated at the board's edge), whereas two (both scolytines; 45 and 522 cm^2) had what seemed to be complete gallery systems (i.e., both parent and larval galleries were complete and not truncated). For the two patches with partial scolytine galleries, one live larva was present in each of the 16-cm^2 and 261-cm^2 bark patches. The 261-cm^2 patch also had a few dead *O. erosus* adults that probably were parent adults. Similarly, for the two patches with complete scolytine galleries, six live larvae were under the 45-cm^2 patch and 10 live brood adults were under the 522-cm^2 patch. An additional live insect was found under a bark patch but was not considered of quarantine importance. It was a single pupa identified as a member of the superfamily Cucujoidea (Coleoptera). This insect was recovered in Seattle, WA, under a 12-cm^2 bark patch with a partial larval gallery on marked crating from China that was associated with tiles.

Overall, we estimated that 0.11% of marked WPM entering the United States during the survey period contained live borers. This value was calculated by multiplying the percentage of WPM with bark (9.4%; 560/5,945) by the percentage of WPM items with bark that harbored live borers (1.2%; 7/564).

Discussion

Our studies in 2004–2006 demonstrated that under favorable field conditions, bark- and wood-infesting insects of quarantine significance can infest and successfully reproduce in logs and boards with residual bark after heat treatment. Broadly similar findings based on both field and laboratory studies were reported by researchers in Canada (Leland Humble, personal communication), Germany (Thomas Schroeder, personal communication), and the United Kingdom (Evans 2007). Each of these studies, all of which were conducted under the auspices of IFQRG, documented posttreatment borer colonization of logs and lumber with residual bark.

We noted that heat treatment itself influenced scolytine colonization and species composition. In the log study, ambrosia beetles dominated on heat-treated barked logs of all four tree species tested, and in both the pine log and board studies, the bark beetle *O. caelatus* was most numerous on heat-treated wood,

Table 7. Number of WPM items with bark that were inspected for live insect borers, no. and type of WPM items with live borers under the bark patches, and the insect family of the borers encountered at six U.S. ports-of-entry in 2006

Port-of-entry city and state	No. WPM items with bark patches	No. bark patches dissected	No. WPM items with live borers under bark	Type of WPM with live borers[a]	Insect family of live borers present under bark[b]
Detroit, MI	203	230	0		
Elizabeth, NJ	65	81	0		
Laredo, TX	97	97	0		
Long Beach, CA	77	77	2	C-2	BOS-1, CER-1
Savannah, GA	50	106	5	C-4, P-1	BOS-1, SCO-4
Seattle, WA	72	108	0		
Total	564	699	7	C-6, P-1	BOS-2. CER-1, SCO-4

[a] C, crating; P, pallets, followed by the number of WPM items with live borers.
[b] BOS, Bostrichidae; CER, Cerambycidae; SCO, Scolytinae, followed by the no. of WPM items that contained those borers.

whereas *I. grandicollis* dominated on untreated wood. Similarly, in the study by Evans (2007) in the United Kingdom using barked pine logs and boards, the bark beetles *Hylurgops palliatus* (Gyllenhal) and *Orthotomicus laricis* Ferrari dominated on heat-treated wood, whereas *Tomicus piniperda* (L.) was most common on untreated controls. It is interesting that each of these five bark beetle species has been intercepted frequently on WPM worldwide and they all have become established beyond their native ranges (Haack 2001, 2006; Brockerhoff et al. 2006).

We found that the shape of the bark patch influenced borer development and survival given that bark beetles completed development in square 100-cm^2 bark patches (10 by 10 cm) but not in rectangular 100-cm^2 bark patches (2.5 by 40 cm). Because adult bark beetles vary greatly in body size ($\approx$ 0.6–10 mm in length) and in the size and orientation of their gallery systems (Wood 1982, Pfeffer 1995), it is reasonable to expect patch shape to influence bark beetle gallery construction and brood development. For example, consider the two Eurasian spruce (*Picea*)-infesting bark beetles, *Ips typographus* (L.) and *Pityogenes chalcographus* (L.) that are commonly intercepted in WPM at U.S. ports (Haack 2001). Both species are harem polygamous, i.e., one male is joined by two or more females, each of which constructs an individual egg gallery. *I. typographus* adults usually are 4.2–5.5 mm in length and their egg galleries are 10–20 cm in length. However, *P. chalcographus* adults are much smaller (1.8–2.5 mm in length), and their egg galleries are shorter (3–5 cm) (Pfeffer 1995). Given these differences in body size and gallery length, a relatively small bark patch (e.g., 10 by 10 cm) would be less constraining to the smaller *P. chalcographus* than the larger *I. typographus.* These potential constraints to colonization and brood development are reflected in the U.S. interception data in that from 1985 through 2000, *P. chalcographus* was the most commonly intercepted scolytine at U.S. ports (565 reported interceptions), whereas *I. typographus* was the fourth most commonly intercepted scolytine (286) (Haack 2001). The second and third most commonly intercepted scolytines were *Orthotomicus erosus* (Wollaston) (385 interceptions; 2.7–3.5 mm in length) and *Hylurgops palliatus* (Gyllenhal) (295 interceptions; 2.5–3.2 mm in length) (Pfeffer 1995, Haack 2001).

Bark-patch size was also an important factor in successful borer development. Although bark beetles and cerambycids infested all sizes of bark patches in our studies, none completed development and emerged on the smallest size tested (25 cm^2). This is not surprising because bark beetles require space for gallery construction by both parent adults and larvae. By contrast, the usually much larger cerambycid larvae probably would require larger bark patches to complete development unless they tunnel into xylem to complete development. It is possible that some of the smallest pine-infesting bark beetles could develop in 25-cm^2 bark patches. For example, *Crypturgus* adults generally are 0.9–1.5 mm in length and construct galleries 1–3 cm in length (Wood 1982, Jordal and Knížek 2007). *Crypturgus pusillus* (Gyllenhal), native to Eurasia, is the only known species of *Crypturgus* to become established outside its native range. It was first reported in eastern North America in 1868 (Wood 1982, Haack 2001, Brockerhoff et al. 2006). Besides limited surface area for insect development, smaller bark patches likely dry faster than larger patches, resulting in reduced nutritional quality for bark-infesting insects (Haack and Slansky 1987).

In this study, all bark beetles and cerambycids initiated colonization in the actual bark patches rather than in bark-free portions of the lumber. This is not surprising because true (i.e., phloeophagous) bark beetles construct their galleries in the inner bark (phloem), and most tree-infesting cerambycids oviposit on or beneath the bark rather than directly on exposed wood (Craighead 1923, Linsley 1959, Haack and Slansky 1987). Therefore, if no residual bark had been present on the wood in our studies, no bark beetles or cerambycids would likely have developed. However, it should be noted that many species of ambrosia beetles infest directly into bark-free portions of wood. For example, McLean and Borden (1977) reported that three species of ambrosia beetles infested directly into bark-free, freshly sawn coniferous lumber, and that colonization rates decreased as the wood dried. Similarly, in our board study, most of the ambrosia beetles entered through the sapwood surface where bark had been removed, but all galleries were later abandoned.

Soon after passage of ISPM 15 in 2002, several countries raised concerns that without complete bark removal, ISPM 15-treated WPM may continue to pose a phytosanitary risk because insects of quarantine significance may infest residual bark after treatment (Evans 2007). IFQRG took the lead in addressing this concern, which led to our study and three others (Evans 2007). The results of the four IFQRG sanctioned studies in part led the Technical Panel on Forest Quarantine, a technical expert group that reports to the IPPC's Standards Committee on forest quarantine issues to recommend tolerance limits on the maximum allowable size of bark patches. This recommendation was incorporated in the 2008 draft revision of ISPM 15 (FAO 2008). With respect to bark, the proposed revision of ISPM 15 allows for any number of small pieces of bark to remain on WPM if they are <3 cm in width (regardless of the length) or if >3 cm in width, with the total surface area of an individual piece of bark <50 cm^2 (FAO 2008). The draft revision of ISPM 15 was discussed and adopted by the Commission on Phytosanitary Measures in April 2009.

With respect to the proposed 50-cm^2 tolerance limit for bark patch size (i.e., the approximate size of a credit card), four of the seven bark patches with live insects found in our port survey were <50 cm^2, indicating that bark patches smaller than a credit card still can harbor live insects. However, it is not known how many of the live individuals would have completed development and emerged as adults. As mentioned, the four WPM items with live scolytines were found in the same shipping container and may have been infested at about the same time. However, brood adults were found only in the largest of the four patches (522 cm^2), whereas larvae were found in the three smaller patches (16, 45, and 261 cm^2).

Although our study and the other IFQRG-related investigations (Evans 2007) showed that insects can colonize treated logs and boards with residual bark under ideal field and laboratory conditions, there remained the question as to how often live insects would be found on ISPM l5-treated WPM with residual bark in actual international trade. Our survey revealed that ≈0.1% of the ISPM 15-marked WPM contained live insects of quarantine significance, which is broadly similar to the results of surveys conducted in Australia (0.4%) and the European Union (0.3%) (Evans 2007, Zahid et al. 2008).

Although all seven WPM items with live borers in our study originated from a single country, we believe that any nation could have been the source of these insects. For example, in surveys conducted in Chile during 2005–2007, live bark- and wood-infesting insects were found in ISPM 15-marked WPM from Brazil, Canada, China, the Netherlands, Spain, and the United States (SAG 2007). Similarly, in surveys of ISPM 15-marked WPM conducted in Australia in 2005–2006, issues of quarantine concern including live pests and bark (Australia currently prohibits WPM with bark) were found on WPM from nine countries (Zahid et al. 2008). Of the 19,522 WPM items inspected in Australia in 2005 (Zahid et al. 2008), 8.5% had bark, which is very similar to our finding of 9.4% in the current study.

Of the seven bark patches in our survey with live borers, two patches had apparently complete (bark beetle) gallery systems and five had partial (i.e., truncated) galleries. Initially, it seems logical that bark patches with live borers and complete galleries would indicate posttreatment infestation because most galleries would be truncated during the milling process, especially on thinner boards. By contrast, bark patches with live borers and truncated galleries would likely indicate colonization before milling followed by some type of treatment failure. However, such scenarios are not always so straightforward. For example, some ISPM 15 facilities initially treat larger wood pieces (cants) before milling into smaller boards. Therefore, cants with residual bark could be colonized after treatment and later milled, resulting in bark patches with live borers and truncated galleries. Without knowing the history of each marked board, it is not possible to determine with certitude whether the insects colonized before or after treatment. Given this uncertainty, the detection of live insects in ISPM 15-marked WPM should not be considered as evidence of a failed policy.

ISPM 15 has undoubtedly reduced the incidence of live insects in WPM. Few detailed surveys before initiation of ISPM 15 have documented the incidence of insects in WPM. In a random survey of 2,547 WPM items that represented worldwide imports into New Zealand during 1989–91, Bulman (1992) noted that 2.7% were infested with insects. Considering this percentage representative of the insect infestation rate of WPM before ISPM 15 and 0.1–0.4% as representing approximate infestation rates after implementation of ISPM 15, one could conclude that ISPM 15 has dramatically reduced the incidence of live insects in WPM. In fact, in the introduction to ISPM 15, the scope of the standard is described in terms of reducing the risk of introduction of quarantine pests rather than eliminating the risk totally (FAO 2002). In addition, this apparent reduction in pest incidence should be considered in light of the large number of pallets and other types of WPM produced annually worldwide. For example, in the United States alone there are >4 billion pallets in use with an annual production of >400 million new pallets (Ray et al. 2007). Worldwide, it is estimated that there are over six billion wood pallets in use (Mumford 2002) with over 1.5 billion replaced annually (TIMCOM 2009).

Many factors can help explain why live insects still are found in ISPM 15-treated WPM. First, as described here, certain insects can colonize and develop in wood after treatment, especially when the wood is from recently cut trees and bark is present. Second, the approved treatments in ISPM 15 may be ineffective in killing all insects, e.g., some species may be heat tolerant (McCullough et al. 2007). Third, it is possible that some treatments are improperly applied, either knowingly or because of faulty equipment or facilities. Nevertheless, even if some insects were introduced via ISPM 15-compliant WPM, arriving insect populations likely will be relatively small. Thus, Allee effects may adversely affect these smaller populations, resulting in a lower probability of successful establishment (Evans 2007, Liebhold and Tobin 2008).

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