Wood packaging material (WPM; e.g., pallets and crates) 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 administered 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...
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 for forest infestation along the trunk. The shape of the small (25 cm²) bark patches was measured, and the number of cerambycids by the log surface area.

On 21 July after 34 d exposure in the field, 24 of the 48 logs (three logs for each tree species × treatment combination) 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 heated separately from the 10-cm-thick boards. Kiln heated boards were open for 30 min) and half served as untreated controls. The 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 August. The first pair of boards was elevated above the forest floor—two boards of similar treatment per category: 1) no bark found, 2) smaller than a credit card (approx. 45 cm²), 3) larger than a credit card but smaller than a standard sheet of typing paper (approx. 600 cm²), 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.

**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 *Xylopterinus*) 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
boards of two thicknesses and four bark classes. 

2005 after exposure to winter temperatures. In the 2005–2006 lumber study June–July 2004. The others were removed from the field in February 34 d in the field during treatment. Half of the logs were removed after 34 d in the field during

Pinus resinosa

Quercus rubra

Acer rubrum

Acanthocinus obsoletus

Orthotomicus caelatus

Hylastes opacus

Dryocoetes autographus

Monochamus notatus

Xyleborinus saxeseni

Polygraphus rufipennis

Orthotomicus caelatus

Monarthrum mali

Gnathotrichus materiarius

CER:

CER:

CER:

CER:

CER:

CER:

Acanthocinus obsoletus

Monochamus notatus

Gnathotrichus materiarius

Orthotomicus caelatus

Monarthrum mali

Xylosandrus germanus

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 speciesa No. collected by study Heat-treated Control

Acer rubrum 2004–2005 log study

CER: Urographus fasciatus (DeGeer) 21 4

SCO: Gaathotrichus materius (Fitch) 1 2

SCO: Monarthrum mali (Fitch) 191 1

SCO: Xylosandrus germanus (Blandford) 35 4

Carya glabra 2004–2005 log study

CER: Saperda dissecta F. 0 1

CER: Urographus fasciatus (DeGeer) 16 0

CER: Xylotrechus colonus (F.) 14 3

SCO: Monarthrum fasciatus (Say) 8 0

SCO: Monarthrum mali (Fitch) 72 2

SCO: Xyleborinus saxeseni (Ratzburg) 1 0

SCO: Xylosandrus germanus (Blandford) 349 0

Quercus robur 2004–2005 log study

CER: Urographus fasciatus (DeGeer) 4 19

SCO: Gaathotrichus materius (Fitch) 2 0

SCO: Monarthrum fasciatus (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: Gaathotrichus materius (Fitch) 715 91

SCO: Ips grandicollis (Eichhoff) 16 233

SCO: Monarthrum fasciatus (Say) 4 0

SCO: Monarthrum mali (Fitch) 5 1

SCO: Orthotomicus caelatus (Eichhoff) 1,695 207

SCO: Polygraphus rufigenialis (Kirby) 3 1

SCO: Xyleborinus saxeseni (Ratzburg) 1 0

SCO: Xylosandrus germanus (Blandford) 6 0

Pinus resinosa 2005–2006 lumber study

CER: Monochamus notatus (Drury) 2 1

SCO: Dryocoetes aratus (Ratzburg) 2 1

SCO: Gaathotrichus materius (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 Gaathotrichus, Monochamus, Xyleborinus, Xylosandrus, and Xylotrechus 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, Urographus, 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 cm²) on boards of both thicknesses, complete development did not occur for any borer species on the 25-cm² patches. However, complete development of bark beetles did occur on large bark patches (100 cm²), 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.
logs that were heat-treated and then subjected to natural infestation in Michigan during 2004 and 2005. Of the 560 crating, dunnage, and pallets, ranging from 7% of the occurrence of bark was broadly similar on blocks, whereas 32% had been fumigated (Table 5). 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 at six U.S. ports (Table 5). The 5,945 WPM items where bark was present.

### 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

<table>
<thead>
<tr>
<th>Tree</th>
<th>Insect</th>
<th>Heat Control</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>C. glabra</td>
<td>Ambrosia beetles</td>
<td>543.5 ± 128.0</td>
<td>2.4 ± 2.4</td>
<td>55.3</td>
</tr>
<tr>
<td>A. rubrum</td>
<td>Ambrosia beetles</td>
<td>112.2 ± 18.1</td>
<td>16.4 ± 8.9</td>
<td>13.1</td>
</tr>
<tr>
<td>Q. rubra</td>
<td>Ambrosia beetles</td>
<td>63.9 ± 6.8</td>
<td>21.7 ± 7.4</td>
<td>8.2</td>
</tr>
<tr>
<td>P. resinosa</td>
<td>Ambrosia beetles</td>
<td>268.9 ± 91.2</td>
<td>17.0 ± 15.2</td>
<td>8.8</td>
</tr>
<tr>
<td>Bark beetles</td>
<td>1,320.2 ± 639</td>
<td>429.8 ± 98.6</td>
<td>4.0</td>
<td>0.1163</td>
</tr>
<tr>
<td>I. grandicollis</td>
<td>20.0 ± 20.0</td>
<td>278.7 ± 26.4</td>
<td>9.6</td>
<td>0.0363</td>
</tr>
<tr>
<td>O. caelatus</td>
<td>1,320.3 ± 615.3</td>
<td>151.1 ± 72.5</td>
<td>12.2</td>
<td>0.0022</td>
</tr>
<tr>
<td>Cerambycidae</td>
<td>2.4 ± 2.4</td>
<td>14.7 ± 7.4</td>
<td>1.2</td>
<td>0.3291</td>
</tr>
</tbody>
</table>

Logs in field June to Feb. 2005 (exposed to winter conditions)

<table>
<thead>
<tr>
<th>Tree</th>
<th>Insect</th>
<th>Heat Control</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>C. glabra</td>
<td>Ambrosia beetles</td>
<td>390.1 ± 165.4</td>
<td>0 ± 0</td>
<td>98.6</td>
</tr>
<tr>
<td>A. rubrum</td>
<td>Ambrosia beetles</td>
<td>361.1 ± 28.6</td>
<td>3.6 ± 0.3</td>
<td>3.1</td>
</tr>
<tr>
<td>Q. rubra</td>
<td>Ambrosia beetles</td>
<td>493.9 ± 276.0</td>
<td>2.1 ± 2.1</td>
<td>36.6</td>
</tr>
<tr>
<td>Cerambycidae</td>
<td>27.0 ± 21.1</td>
<td>4.3 ± 4.3</td>
<td>0.9</td>
<td>0.4072</td>
</tr>
<tr>
<td>O. caelatus</td>
<td>9.0 ± 9.0</td>
<td>0 ± 0</td>
<td>1.0</td>
<td>0.3739</td>
</tr>
<tr>
<td>Cerambycidae</td>
<td>3.9 ± 1.9</td>
<td>23.3 ± 5.3</td>
<td>7.3</td>
<td>0.0540</td>
</tr>
<tr>
<td>O. caelatus</td>
<td>421.5 ± 223</td>
<td>80.2 ± 59.8</td>
<td>2.8</td>
<td>0.1671</td>
</tr>
<tr>
<td>Bark beetles</td>
<td>459.8 ± 192</td>
<td>85.6 ± 75.4</td>
<td>1.0</td>
<td>0.1627</td>
</tr>
<tr>
<td>I. grandicollis</td>
<td>0 ± 0</td>
<td>2.4 ± 2.4</td>
<td>1.0</td>
<td>0.3739</td>
</tr>
<tr>
<td>O. caelatus</td>
<td>456.2 ± 191</td>
<td>81.8 ± 73.6</td>
<td>3.1</td>
<td>0.1523</td>
</tr>
<tr>
<td>Cerambycidae</td>
<td>1.2 ± 1.2</td>
<td>13.9 ± 8.4</td>
<td>1.7</td>
<td>0.2633</td>
</tr>
</tbody>
</table>

### 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 at six U.S. ports (Table 5).

### 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

<table>
<thead>
<tr>
<th>Tree</th>
<th>Insect</th>
<th>Heat Control</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>C. glabra</td>
<td>Ambrosia beetles</td>
<td>442.5 ± 49.8</td>
<td>4.7 ± 3.2</td>
<td>79.7</td>
</tr>
<tr>
<td>A. rubrum</td>
<td>Ambrosia beetles</td>
<td>114.0 ± 22.1</td>
<td>61.4 ± 9.8</td>
<td>3.1</td>
</tr>
<tr>
<td>Q. rubra</td>
<td>Ambrosia beetles</td>
<td>31.6 ± 17.9</td>
<td>78.5 ± 43.1</td>
<td>0.03</td>
</tr>
<tr>
<td>P. resinosa</td>
<td>Ambrosia beetles</td>
<td>124.3 ± 16.9</td>
<td>56.3 ± 18.6</td>
<td>5.3</td>
</tr>
<tr>
<td>Cerambycidae</td>
<td>35.0 ± 15.6</td>
<td>117.8 ± 53.4</td>
<td>0.7</td>
<td>0.4146</td>
</tr>
<tr>
<td>F. purpurea</td>
<td>168.2 ± 34.2</td>
<td>4.0 ± 1.6</td>
<td>55.1</td>
<td>0.0001</td>
</tr>
<tr>
<td>Bark beetles</td>
<td>118.1 ± 14.9</td>
<td>69.2 ± 11.2</td>
<td>7.3</td>
<td>0.0224</td>
</tr>
<tr>
<td>I. grandicollis</td>
<td>7.3 ± 3.0</td>
<td>43.1 ± 5.0</td>
<td>21.7</td>
<td>0.0009</td>
</tr>
<tr>
<td>O. caelatus</td>
<td>110.2 ± 13.7</td>
<td>26.0 ± 12.6</td>
<td>10.4</td>
<td>0.0091</td>
</tr>
<tr>
<td>Cerambycidae</td>
<td>9.7 ± 8.2</td>
<td>14.4 ± 8.2</td>
<td>0.3</td>
<td>0.5760</td>
</tr>
</tbody>
</table>

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.
and surface area of the bark patch (between wood-moisture level beneath the bark patch (Table 6). There was no significant linear relation aging, with average values ranging from 13.5 to 17.5% broadly similar among different types of wood pack-
moisture content beneath the bark patches was basis) and averaged 15.9% (Table 6). Mean wood-
df.

The seven WPM items with live borers signified heat treatment, whereas the other ISPM 15 mark on six of the seven WPM items with live borers were detected at two ports (Long Beach, CA and Savannah, GA); all had originated in Turkey live borers were detected at two ports (Long Beach, CA and Savannah, GA); all had originated in Turkey cerambycids, and four had scolytines (Table 7). The items (1.2% of 564 WPM items, 1.0% of 699 bark patch-
beneath seven bark patches on seven distinct WPM
14 Ð25%.
bored live borers, was 17.4 ± 1.3% with a range of 14–25%.

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.

<table>
<thead>
<tr>
<th>Bark patch size</th>
<th>2.5-cm-thick lumber</th>
<th>10-cm-thick lumber</th>
<th>P</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heat</td>
<td>Control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All bark</td>
<td>107.3 ± 42.7 (67%)</td>
<td>88.0 ± 26.5 (67%)</td>
<td>0.99</td>
<td>169.1 ± 37.5 (100%)</td>
</tr>
<tr>
<td>Large patch</td>
<td>72.7 ± 53.3 (53%)</td>
<td>41.7 ± 10.4 (67%)</td>
<td>0.82</td>
<td>141.7 ± 31.9 (83%)</td>
</tr>
<tr>
<td>Small patch</td>
<td>45.3 ± 20.7 (45%)</td>
<td>83.3 ± 21.6 (83%)</td>
<td>0.07</td>
<td>129.0 ± 36.1 (70%)</td>
</tr>
<tr>
<td>Bark free</td>
<td>0 ± 0 (0%)</td>
<td>0 ± 0 (0%)</td>
<td></td>
<td>0 ± 0 (0%)</td>
</tr>
</tbody>
</table>

|                | Heat                | Control            |    |    |
| All bark       | 56.6 ± 56.6 (17%)   | 0 ± 0 (0%)         | 0.34 | 191.3 ± 39.8 (100%) |
| Large patch    | 0 ± 0 (0%)          | 0 ± 0 (0%)         |    | 175.0 ± 57.3 (50%) |
| Small patch    | 0 ± 0 (0%)          | 0 ± 0 (0%)         |    | 0 ± 0 (0%)       |
| Bark free      | 0 ± 0 (0%)          | 0 ± 0 (0%)         |    | 0 ± 0 (0%)       |

|                | Heat                | Control            |    |    |
| All bark       | 115.6 ± 36.3 (75%)  | 110.3 ± 37.5 (83%) | 0.88 | 83.6 ± 14.8 (92%) |
| Large patch    | 163.0 ± 51.8 (73%)  | 116.7 ± 39.1 (55%) | 0.50 | 241.7 ± 61.5 (75%) |
| Small patch    | 168.2 ± 62.6 (64%)  | 100.0 ± 31.4 (55%) | 0.75 | 241.7 ± 73.8 (67%) |
| Bark free      | 0 ± 0 (0%)          | 0 ± 0 (0%)         |    | 0 ± 0 (0%)       |

|                | Heat                | Control            |    |    |
| All bark       | 0 ± 0 (0%)          | 0 ± 0 (0%)         | 7.0 (100%) | 0.05 |
| Large patch    | 0 ± 0 (0%)          | 0 ± 0 (0%)         | 70.0 (50%) | 0.77 |
| Small patch    | 0 ± 0 (0%)          | 0 ± 0 (0%)         | 26.5 (67%) | 0.77 |
| Bark free      | 0 ± 0 (0%)          | 0 ± 0 (0%)         | 31.9 (83%) | 0.77 |

Species of bark- and wood-infesting insects reared from boards are listed in Table 1. Mean gallery density values were based on sample sizes of 11–12 boards. For each comparison (within rows of similar board thickness), df = 1, 9 or 1, 10.

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.

<table>
<thead>
<tr>
<th>WPM type</th>
<th>Total</th>
<th>Size of largest bark patcha (no.)</th>
<th>% with bark</th>
<th>Treatment (no.)b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blocks</td>
<td>47</td>
<td>None 40 0 &lt; 45 cm² 1 5 1 14.9 14.9</td>
<td>0 &lt; 45 cm² 1 5 1 14.9 14.9</td>
<td>HT MB</td>
</tr>
<tr>
<td>Crating</td>
<td>979</td>
<td>None 104 45 &gt; 600 cm² 14 4 16.8 16.8</td>
<td>45 &gt; 600 cm² 14 4 16.8 16.8</td>
<td>MB</td>
</tr>
<tr>
<td>Dummage</td>
<td>3,465</td>
<td>None 131 &gt;600 cm² 2 2 11.1 11.1</td>
<td>&gt;600 cm² 2 2 11.1 11.1</td>
<td>HT MB</td>
</tr>
<tr>
<td>Pallets</td>
<td>1,453</td>
<td>None 79 11.1 11.1</td>
<td>79 2 2 11.1 11.1</td>
<td>MB</td>
</tr>
<tr>
<td>Spool</td>
<td>1</td>
<td>None 0 0</td>
<td>0 0</td>
<td>0 0</td>
</tr>
<tr>
<td>Total</td>
<td>5,945</td>
<td>None 317 11.1 11.1</td>
<td>317 11.1 11.1</td>
<td>HT MB</td>
</tr>
</tbody>
</table>

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 cm²); 3, larger than a credit card but smaller than a standard sheet of paper (≈600 cm²); and 4, larger than a sheet of paper.

b ISPM 15 treatments: HT, heat treatment; MB, methyl bromide fumigation.
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 cerambid 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 cm². The cerambid was under a 120-cm² bark patch. The scolytines were under bark patches of 16, 45, 261, and 522 cm². Five of the seven patches (16, 24, 36, 120, and 261 cm²) with under bark patches of 16, 45, 261, and 522 cm². Five of the seven patches with partial scolytine galleries, one live larva was present in each of the 16-cm² and 261-cm² bark patches. The 261-cm² 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-cm² patch and 10 live brood adults were under the 522-cm² 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-cm² 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).
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-cm² bark patches (10 by 10 cm) but not in rectangular 100-cm² bark patches (2.5 by 40 cm). Because adult bark beetles vary greatly in body size (≈ 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 intercepts; 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 cm²). 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-cm² 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 Knůžek 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., phloemophagous) 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 cm² (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-cm² 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 cm², 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 cm²), whereas larvae were found in the three smaller patches (16, 45, and 261 cm²).

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 15-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 live 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 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 certainty 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).

Acknowledgments

We thank Kyle Brown, Rachel Disipio, D. Pascal Kamdem, Tina Ciarmitaro, Pascal Nzokou, Christopher O’Connor, Amy Wilson, and staff of the W. K. Kellogg Experimental Forest for field and laboratory assistance; Kerry Britton and Roger West for facilitating the port surveys; Marcy Mellors, Henry Guiterrez, Deyanira Mares, William Norris, Diane Panetta, Stephanie Provisnky, and Janelle Tokunaga for assisting with the port surveys; Rodney Burgess, Sonya Hammons, Bjarte Jordal, Lawrence Kirkendall, John McLean, and Shane Sela for technical advice; Leland Humble and Thomas Schroeder for sharing unpublished data; Eric Allen, Kerry Britton, Marty Jones, and two anonymous reviewers for commenting on an earlier draft of this paper; and the USDA Forest Service, Forest Health Protection, and Vegetation Management and Protection Research, for partial funding of the port survey.

References Cited


Received 3 January 2009; accepted 14 March 2009.