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Identification of Tree Genera Used in the Construction of Solid Wood-Packaging Materials That Arrived at U.S. Ports Infested With Live Wood-Boring Insects

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Abstract

Although international regulations have been successfully implemented to reduce the introduction and spread of plant pests through wood packaging material (WPM), wood-boring insects continue to be intercepted in WPM at U.S. ports of entry. Both hardwoods and softwoods are used in the construction of WPM for international trade; however, it is not clear if some types of wood pose higher risks than others for harboring wood borers. This study documented the taxonomic diversity of infested wood genera intercepted as a result of targeted WPM inspection at U.S. ports, and identified many of the wood-boring insects transported within them. The results of this study reveal associations among packaging woods, commodities, and shipment origins. The wood genera most frequently infested were *Pinus* Linnaeus (Pinales: Pinaceae), *Picea* Miller (Pinales: Pinaceae), and *Populus* Linnaeus (Malpighiales: Salicaceae), which were heavily represented as packaging for commodities such as stone, metal, vehicles, and machinery. In addition to these results, we summarized preferences by the wood borers to develop in living, stressed, dying, or dead hosts, the pest status of intercepted wood borers in their native and non-native ranges, and potential host range of intercepted wood borers to gauge potential for these taxa to become pests in North America. New possible host associations are reported for eight wood borer taxa. Taxonomy of host wood is presented as a new factor for consideration in pathway-level risk analysis of WPM, and the findings further reinforce the need for enhanced compliance with ISPM 15 to reduce entry of non-native wood-boring insects.

Key words: Cerambycidae, Buprestidae, Siricidae, host association, invasive species

Solid wood packaging material (WPM) is one of the most important pathways facilitating long-distance invasions of forest pests, especially wood-boring insects (Aukema et al. 2010). Considerable efforts have been made in recent years to reduce the likelihood of movement of pests, including development of International Standards for Phytosanitary Measures No. 15 (ISPM 15). These standards were implemented in 2002 by the International Plant Protection Convention (IPPC) to reduce the risk of arrival of plant pests and diseases through unprocessed wood. The United States adopted ISPM 15 in 2005 (Haack et al. 2014).

Wood packaging material most often takes the form of pallets, dunnage, crates, boxes, packing cases, cable drums, and spools. According to ISPM 15, all solid wood used to construct WPM must be debarked to eliminate or reduce infestation by wood pests that require bark for development (Haack and Petrice 2009), although a low tolerance (<3 cm wide or <50 cm^2 per piece) for residual bark is allowed. Following debarking, wood is subjected to phytosanitary heat or fumigation treatment to reduce the risk of introduction of insects and plant pathogens through unprocessed raw wood. The treated WPM must be certified with a legible and permanent mark (i.e., the ISPM 15 mark) approved by IPPC (2018). Wood packaging made of processed materials, such as plywood and presswood, are exempt from phytosanitary treatment (IPPC 2018). Budgetary or other constraints on certifying agencies may prevent monitoring and enforcement of phytosanitary treatment, however, and pests may infest the wood after treatment. To reduce risks of introduction, shipments of

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consignments are regularly inspected at ports of entry to ensure compliance with ISPM standards (Haack et al. 2014). Noncompliance includes WPM with missing or counterfeit ISPM 15 marks, WPM with excessive bark (see above), and WPM infested with live pests of wood. Inspection of wood packaging is targeted toward consignments that may have a history of noncompliance with ISPM 15 by exporting companies and their WPM-treatment facilities, or by particular exporting regions. Wood packaging for heavy products, including stone, metal, and machinery, is often targeted for inspection because these products are historically associated with higher risk for wood borer infestation (Haack 2006, Eyre and Haack 2017, Eyre et al. 2018).

Although WPM inspection in the United States is targeted toward consignments deemed at risk of harboring pests, in practice only 2% or less of cargo is inspected (National Research Council 2002). Inspection is performed on all individual wood-packaging items in a targeted consignment, regardless of form. Wood-boring insects present a special challenge for inspection because they feed inside wood, and their presence may not always be indicated by external signs (Humble 2010). Therefore, wood-boring insects may have entered the United States and elsewhere through the WPM pathway before the implementation of ISPM 15 and possibly also after (Meurisse et al. 2019).

Both hardwoods (angiosperms) and softwoods (gymnosperms, conifers) are used in the construction of WPM (Allen and Humble 2002). Information is lacking, however, on whether one of these groups poses a higher risk for transporting live wood-boring insects and if any wood taxa are more common hosts. During a recent study to identify wood-boring insects intercepted in WPM at U.S. ports of entry (Wu et al. 2017), we gathered samples of infested wood (henceforth referred to as 'host wood') with the goal of identifying the wood to genus. Our primary aim was to document taxa of trees used to manufacture WPM that is found with live insects at U.S. ports and to document the wood borers found within them. We hoped to learn whether some taxa of wood used as packaging are more likely than others to harbor infestations and whether these infestations are linked to shipment origins. The focus was on insects in the wood borer families Cerambycidae and Buprestidae (Coleoptera), and Siricidae (Hymenoptera). We identified insects using molecular techniques and by rearing of intercepted larvae to the adult stage (see Wu et al. 2017). Once insects were identified, we compiled host-utilization traits that could suggest their potential to become pests outside their native ranges.

Due to nonrandom inspection of incoming cargo and WPM performed at U.S. ports, our report is largely descriptive. The number of infested wood samples available for this study depended on the number of port inspections targeted and the number of live wood borers found, and may have been influenced by other variables such as time available to inspectors for cutting wood samples. Nevertheless, to our knowledge, we offer the first account of some of the diversity of packaging woods intercepted with wood-boring insects. Identification of infested host wood genera and their associated wood borers provides useful information for predicting which species of native trees may be vulnerable to attack by translocated insects. Links revealed among wood taxa, shipment origins, and commodity categories may also be useful for confirming or refining current inspection strategies for WPM.

Materials and Methods

Collection and Identification of WPM and Wood-Boring Insects

Between April 2012 and January 2018, we participated in a collaborative project between the U.S. Department of Homeland Security Customs and Border Protection (CBP) and the U.S. Department of Agriculture Animal and Plant Health Inspection Service (USDA APHIS) to identify live cerambycids and buprestids intercepted at several U.S. ports in WPM (see Wu et al. 2017). During 2016–2017, the project was expanded to include siricids. At the same time, we gathered and identified infested host wood samples. Collection of insect and wood specimens initially involved CBP and APHIS participants from six U.S. ports and expanded to 11 ports by 2016. The first six ports (Houston, Hidalgo-Pharr, and Laredo in Texas; Long Beach in California; Seattle-Tacoma in Washington; and Detroit in Michigan) were selected based on a combination of location and history of frequent cerambycid and buprestid interceptions. Seattle-Tacoma began sending specimens in 2012, whereas others began in early 2013. Miami and Port Everglades in Florida were added to the study in early 2014, and the last three ports, San Diego and San Francisco in California, and Chicago in Illinois, were added in 2015. The ports handle maritime and air cargo except the land ports of Hidalgo-Pharr and Laredo on the Mexican border and the sea ports of Long Beach and Port Everglades. Live insect specimens were collected by CBP personnel and brought to APHIS Plant Inspection Stations for identification of pest group. The samples were shipped in coolers with ice packs to the containment facility at the USDA APHIS Plant Protection and Quarantine (PPQ), Science and Technology, Otis Laboratory (Buzzards Bay, MA) for rearing, followed by genus- or species-level identification using morphological and molecular methods (see Wu et al. 2017 for details). When possible, the specimens, usually larvae, were shipped in host wood to complete development in the wood. Larvae sent without host wood were either preserved or reared on an artificial diet, and they are excluded from this report. Upon emergence, adults were freeze-killed and shipped to the USDA Systematic Entomology Laboratory (Beltsville, MD) for identification based on morphology. Legs and/or antennae sampled from adults, and larval specimens that died during rearing attempts, were preserved in 95% ethanol for DNA analysis. Attempts were made at the Otis Laboratory to obtain DNA (CO1) barcode sequences for all wood borer specimens. These were queried against CO1 sequences in the Barcode of Life Database v4 (BOLD; last queried on 19 January 2019) for species identification (Hebert et al. 2003). Identification results were confirmed by BLAST searches in GenBank's nucleotide database. Wu et al. (2017) provide details on the divergence thresholds used and on the handling of inconclusive identifications. Briefly, we considered divergence from a reference barcode of 2–3% to be congeneric and below 1% as conspecific. *Monochamus sartor* (Fabricius) and *M. urussovii* (Fischer von Waldheim) (Coleoptera: Cerambycidae) were recently confirmed to be subspecies of *M. sartor* (Plewa et al. 2018), but we retained their species designations for this report. *Anastrangalia reyi* (Heyden) (Coleoptera: Cerambycidae), which was recently confirmed to be a subspecies of *Anastrangalia dubia* (Scopoli) (Coleoptera: Cerambycidae) (Zamoroka et al. 2019), is herein classified as *A. dubia*. The Nearctic subspecies *Arhopalus rusticus montanus* (LeConte) (Coleoptera: Cerambycidae) is herein classified as *A. montanus* (LeConte) (Coleoptera: Cerambycidae) (Bosquet et al. 2017). Voucher specimens of adults, larvae (if relatively intact after DNA extraction), and DNA tissue are deposited at the APHIS PPQ S&T Otis Laboratory.

Host wood samples were identified to genus based on a combination of physical and anatomical characters. Identification to species level was not attempted because, in the absence of additional materials such as bark, fruit, or flowers, wood samples are generally identifiable only to genus. Wood voucher specimens are deposited at the APHIS PPQ S&T Otis Laboratory.

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Commodity, Shipment Origin, WPM Type, and Phytosanitary Treatment

Interception and phytosanitary treatment data were compiled from PPQ pest interception forms (PPQ form 309A and Diagnostic Request forms) and from the PPQ Emergency Action Notification (EAN) system database. Pest interception forms were created by APHIS personnel at the ports of entry for each interception of live pests, and the data, including the eventual taxonomic determination, are entered into the USDA APHIS Pest Interception Database (PestID). Inspections without pest finds are not usually recorded. We compiled the following data from these databases: country of origin of the shipment, the commodity associated with the infested WPM, the type of wood packaging (pallet, crating, etc.), and details of the ISPM 15 treatment. The ISPM 15 mark (if present) includes country and facility codes identifying where the WPM was treated, and the type of treatment applied. Complete data for each interception were not always available. To summarize commodity data and the types of packaging and woods associated with them, we consolidated 48 reported consignment types (retrieved from the EAN database) into 16 broader categories containing similar products (see Table 2 for details). For example, all consignments containing stone, stone products, ceramic tiles, terracotta, and sanitary fixtures (porcelain) were grouped into a category called Stone, Ceramics, and Terracotta; raw metals, metal products, and stranded wire were grouped into a Metal category; and fruits, vegetables, herbs, seeds, and frozen or dried foods were grouped into Fresh Produce, Herbs, and Seeds.

Host Wood–Insect Associations, Developmental-Host Range, and Pest Status

The identified host woods were compared with published host records for each insect species to determine whether the developmental (larval) hosts were known or potentially new. Care was taken to accept only records that clearly associated the larval stage with the host plant and to exclude records for adult food plants or undefined associations. We also examined the literature for accounts of the diet breadth (developmental-host range) of identified wood borers, grouping them into three categories defined by Haack (2017) as monophagous: larval feeding on one or more species within a single plant genus; oligophagous: larval feeding on two or more host genera within a single plant family; and polyphagous: larval feeding on species in two or more plant families. These were compiled along with records of other biological traits: preference for larval development in healthy, stressed, or dead hosts; native, absent, or non-native but present status in the United States, and pest status throughout the native and non-native range. We recognized four categories of tree condition preferred by the borers as larval hosts (modified from Hanks 1999): living hosts (LH), ranging from healthy to moderately stressed but with recovery possible once the cause of stress (e.g., drought) is eliminated; severely stressed hosts (SH) with no chance of recovery once the stress factor is eliminated; dead, recently felled hosts (DH); and dry wood (DW), including seasoned or decaying wood. Because pests of living trees (LH) are harmful not only to the health of the trees but also to the utility of the wood, their damage potential was considered high, which we designated Group A, while pests in the SH, DH, and DW groups were placed in a lower damage-potential category, designated Group B. Native U.S. wood borer species were considered nonpests although they may become pests if spreading outside their native ranges.

Results

Identification of Host Woods and Shipment Origins

Between April 2012 and January 2018, 516 infested wood samples were collected from five world regions through participating U.S. ports. Of these, 36 were unidentifiable, largely because they consisted only of bark or inadequate amounts of material, and are excluded from this analysis. We classified 480 samples as hardwoods (angiosperm trees) or softwoods (conifer trees) and identified them to genus (Table 1). The WPM was constructed mostly of softwoods (79%). Five softwood genera belonging to two plant families and 31 hardwood genera belonging to 17 families were recognized. Although a higher diversity was identified in hardwoods, most of them (20) were encountered only once. Among the identified wood genera, the most frequently found to be infested with wood borers were *Pinus* Linnaeus (Pinales: Pinaceae) (263 interceptions, 55%), *Picea* Miller (Pinales: Pinaceae) (92 interceptions, 19%), and *Populus* Linnaeus (Malpighiales: Salicaceae) (48 interceptions, 10%). Wood samples came from consignments originating from 42 countries. Softwood samples originated nearly equally from Asia (33%), Europe (35%), and North America (Mexico; 31%), whereas hardwood samples originated predominantly from Asia (84%). The majority of WPM interceptions containing live wood borers were from Mexico, China, and Turkey; these countries contributed 24, 20, and 14%, respectively, of the interceptions for which we compiled taxonomic data on both the host wood and wood borers.

Wood Taxa Represented in Packaging Types, and Associated Commodities

Nearly half the records specified infested wood packaging as crating, dunnage, or pallets, whereas the remainder was recorded only as unspecified WPM (Table 2). Pallets were constructed mostly of softwoods (86%), specifically of *Pinus* and *Picea* wood. Crating was constructed of both hardwoods and softwoods, and dunnage was made of softwoods, but sample sizes for these specified packaging forms were too limited to include in a meaningful summary. Four broad commodity categories were associated with the majority (82%) of infested WPM: Stone, Ceramics, and Terracotta; Vehicles and Vehicle Parts; Machinery, Tools, and Hardware; and Metal (Table 2). Both softwoods and hardwoods were more frequently associated with these commodities than with other commodities. Of 378 interceptions of softwoods linked with commodity data, 80% were associated with these four commodity categories, while 88% of 102 hardwood interceptions were associated with them.

Packaging woods associated with the above commodity categories are summarized for the three countries of origin most heavily represented by infested wood (Table 3). The infested WPM from Mexico and Turkey was represented only by softwood tree genera, whereas mostly hardwoods were represented in infested WPM from China. *Populus* was the dominant hardwood genus intercepted from China, represented in 40 (62%) of 64 hardwood interceptions; 21 of the *Populus* interceptions were associated with stone, ceramic, and terracotta commodities. *Pinus* comprised 99% of the WPM identified from Mexico, whereas *Picea* was the dominant genus (52%) from Turkey.

Identification of Insects and Host Wood–Insect Associations

Specimens of 444 wood borers were identified to genus or species from 432 wood samples identified to genus (Supp Table 1 [online only]). They comprised 388 cerambycids, 45 buprestids, and 11 siricids. An additional 271 cerambycids, 61 buprestids, and seven

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Table 1. Genera of tree species used to construct wood packaging that was found infested with live wood borers at U.S. ports of entry during 2012–2018, number of infested samples, and world regions from which consignments originated

Plant group, family, genus	Origin of imported consignments						
	Africa	Asia	Central and South America	Europe	North America (Mexico)	Unknown	Total
Hardwoods (angiosperm trees)							
Anacardiaceae (Sapindales)							
Mangifera Linnaeus		10					10
Pistacia Linnaeus		1					1
Araliaceae (Apiales)							
Schefflera J.R. Forster & G. Forster		1					1
Betulaceae (Fagales)							
Alnus Miller				2			2
Betula Linnaeus				1			1
Bignoniaceae (Lamiales)							
Catalpa Scopoli		1					1
Tabebuia Gomes ex A.P. de Candolle		1					1
Dipterocarpaceae (Malvales)							
Shorea Roxburgh ex C.F. Gaertner		1					1
Ebenaceae (Ericales)							
Diospyros Linnaeus		3					3
Euphorbiaceae (Malpighiales)							
Aleurites J.R. Forster & G. Forster		2					2
Hevea Aublet		3					3
Melanolepis? Reichenbach f. & Zollinger		1					1
Fabaceae (Fabales)							
Acacia Martius		4	1				5
Cassia Linnaeus		1					1
Enterolobium Martius			1				1
Lonchocarpus Kunth		1					1
Parkia R. Brown		1					1
Fagaceae (Fagales)							
Castanopsis (D. Don) Spach		2					2
Fagus Linnaeus				2			2
Quercus Linnaeus		2					2
Meliaceae (Sapindales)							
Melia Linnaeus		1					1
Moraceae (Rosales)							
Ficus Linnaeus		1					1
Artocarpus J.R. Forster & G. Forster		1					1
Myrtaceae (Myrtales)							
Eucalyptus L'Héritier		2	1				3
Syzygium R. Brown ex Gaertner		1					1
Rutaceae (Sapindales)							
Phellodendron Ruprecht		1					1
Salicaceae (Malpighiales)							
Populus Linnaeus		40		8			48
Sapotaceae (Ericales)							
Pouteria Aublet		1					1
Symplocaceae (Ericales)							
Symplocos Jacquin		1					1
Ulmaceae (Rosales)							
Ulmus Linnaeus		1					1
Holoptelea Planchon		1					1
Hardwood total		**86**	**3**	**13**			**102**
Softwoods (conifer trees)							
Cupressaceae (Pinales)							
Cupressus Linnaeus				1			1
Pinaceae (Pinales)							
Abies Miller		7		11			18
Picea Miller	1	45		46	1		93
Pinus Linnaeus	1	72	2	70	116	2	263
Pseudotsuga Carrière				3			3
Softwood total	**2**	**124**	**2**	**131**	**117**	**2**	**378**
Total	**2**	**210**	**5**	**144**	**117**	**2**	**480**

Values in bold denote totals and subtotals.

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Table 2. Number of interceptions of live wood borers made at selected U.S. ports of entry in wood packaging material (WPM) associated with imported goods during 2012–2018 by WPM type, WPM genus, and associated imported commodities

	Commodities																
Packaging form, wood group, wood genus	Stone, Ceramics, Terracotta	Vehicles and Vehicle Parts	Machinery, Tools, Hardware	Metal	Fresh Produce, Herbs, Seeds	Commodity Unknown	Plastics	Rubber	Wood Products	Glass	Elec-tronics	Nonregulated Processed Food and Beverage	Misc. Animal Products	Misc. Personal Products	Paper	Textiles	Total
Crating	7	1	1	1	1	1											12
Hardwood	4	1		1													6
Aleurites	1																1
Populus	2																2
Syzygium		1															1
Tabebuia				1													1
Ulmus	1																1
Softwood	3		1		1	1											6
Picea	1		1		1												3
Pinus	2					1											3
Dunnage		1	1	2		2											6
Softwood		1	1	2		2											6
Picea			1														1
Pinus		1		2		2											5
Pallets	35	70	40	23	9	6	8	3	5	2	1	1	2	1	1	1	209
Hardwood	10	9	4	2			1	1		1	1						29
Acacia		1						1									2
Alnus		1															1
Betula		1															1
Castanopsis							1										1
Catalpa	1																1
Enterolobium	1																1
Eucalyptus											1						1
Hevea			1														1
Lonchocarpus	1																1
Mangifera	1	1		1													3
Melanolepis?	1																1
Phellodendron			1														1
Populus	5	5	2	1						1							14
Softwood	25	62	36	21	9	6	7	2	5	1		1	2	1	1	1	180
Abies	1	3	3	2		1	1					1					12
Picea	6	24	6	4		5	2									1	48
Pinus	18	32	27	15	9		4	2	5	1			2	1	1		117
Pseudotsuga		3															3
Unspecified WPM	108	26	36	41	8	8	6	5	3	4	4	3	1				253
Hardwood	34	4	6	15	2	1	1	1		1	1	1					67
Acacia			1	1	1												3
Aleurites	1																1
Alnus	1																1
Artocarpus	1																1
Betula		1															1

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Table 2. Continued

Packaging form, wood group, wood genus	Commodities: Stone, Ceramics, Terracotta	Vehicles and Vehicle Parts	Machinery, Tools, Hardware	Metal	Fresh Produce, Herbs, Seeds	Commodity Unknown	Plastics	Rubber	Wood Products	Glass	Elec-tronics	Nonregulated Processed Food and Beverage	Misc. Animal Products	Misc. Personal Products	Paper	Textiles	Total
Cassia		1															1
Castanopsis	1																1
Diospyros	3																3
Eucalyptus	1										1						2
Fagus		1	1														2
Ficus	1																1
Hevea	2																2
Holoptelea				1													1
Mangifera	3		1	3													7
Melia		1															1
Parkia	1																1
Pistacia	1																1
Populus	15	1	2	9	1	1		1		1		1					32
Pouteria							1										1
Quercus	1			1													2
Schefflera	1																1
Shorea			1														1
Symplocos	1																1
Softwood	**74**	**22**	**30**	**26**	**6**	**7**	**5**	**4**	**3**	**3**	**3**	**2**	**1**				**186**
Abies	2	1		1		1	1										6
Cupressus	1																1
Picea	27	4		2	1	1	2			1		2	1				41
Pinus	44	17	30	23	5	5	2	4	3	2	3						138
Total	**150**	**99**	**78**	**67**	**18**	**17**	**14**	**8**	**8**	**6**	**5**	**4**	**3**	**1**	**1**	**1**	**480**

Commodity categories were condensed from categories reported in the EAN database as follows: Electronics includes electronics and electric components, equipment; Fresh Produce, Herbs, Seeds includes a variety of vegetables, fruits, sunflower, ginger root; Glass includes glass and glass products; Machinery, Tools, Hardware includes machinery and machine parts, construction tools, hardware; Metal includes metal products and raw metals, aluminum, stranded wire; Misc. Animal Products includes animal products, beeswax; Misc. Personal includes personal effects; Non-Regulated Processed Food and Beverage is self-explanatory; Paper includes paper and paper products; Plastics includes plastics and plastic products; Rubber includes rubber and rubber products, consolidation—not further defined; Stone, Ceramics, Terracotta includes Stone products—ceramic tile, tiles, other stone products, marble slabs, granite, terracotta products, sanitary fixtures, household goods—ceramic; Textiles includes textiles and apparel; Unknown is self-explanatory; Vehicles and Parts includes automobile parts, used vehicles, farm/construction equipment, vehicle spare parts, maritime vessels; Wood Products includes manifested pallets/crates/spools (not WPM), handicrafts or art made of natural materials, *Quercus* sp.

Values in bold denote totals and subtotals for type of WPM and for wood groups.

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Table 3. Number of interceptions of live wood borers made at selected U.S. ports of entry in wood packaging material (WPM) during 2012–2018 that were associated with imported goods from China, Mexico, and Turkey, by host-wood genus and associated imported commodities

	Commodities														
Origin, wood group, genus	Stone, Ceramics, Terracotta	Machinery, Tools, Hardware	Vehicles and Parts	Metal	Fresh Produce, Herbs, Seeds	Plastics	Wood Products	Glass	Rubber	Electronics	Misc. Animal Products	Nonregulated Processed Food and Beverage	Commodity Unknown	Paper	Total
China															
Hardwood	**38**	**6**	**2**	**11**	**1**	**2**		**2**	**1**			**1**			**64**
Aleurites	2														2
Castanopsis	1					1									2
Catalpa	1														1
Diospyros	3														3
Ficus	1														1
Hevea	1	1													2
Lonchocarpus	1														1
Mangifera	1	1													2
Melanolepis?	1														1
Melia			1												1
Phellodendron		1													1
Pistacia	1														1
Populus	21	3	1	10	1			2	1			1			40
Pouteria						1									1
Quercus	1			1											2
Schefflera	1														1
Symplocos	1														1
Ulmus	1														1
Softwood	**11**	**10**	**4**	**6**				**1**		**1**	**1**				**34**
Abies	1	1													2
Picea		1									1				2
Pinus	10	8	4	6				1		1					30
Mexico															
Softwood	**7**	**40**	**22**	**17**	**13**	**2**	**8**	**2**		**2**	**2**		**1**	**1**	**117**
Picea					1										1
Pinus	7	40	22	17	12	2	8	2		2	2		1	1	**116**
Turkey															
Softwood	**36**	**1**	**17**	**4**	**1**	**4**			**3**			**1**	**1**		**68**
Abies			2			1						1			4
Picea	24		7		1	3									35
Pinus	12	1	8	4					3				1		29
Total	**92**	**57**	**45**	**38**	**15**	**8**	**8**	**5**	**4**	**3**	**3**	**2**	**2**	**1**	**283**

Commodity categories were condensed from categories reported in the EAN database (details in Table 2).
Values in bold denote totals and subtotals.

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siricids from identified wood were classified to family level only. Multiple conspecific specimens, and, in some cases, multiple species of insects, were occasionally collected from a single item of wood packaging. We note that in two cases, two wood genera were submitted as a single sample and the host wood–insect association was determined based on published host records. More than one type of wood is often used in a single pallet or crate, which are made of several pieces. We also note that, in a few cases, the DNA barcode sequences of particular insect specimens shared >99% sequence identities with more than one named species in BOLD and we therefore classified these to genus level only. Hundreds of additional insects from other interceptions were forwarded to us from the ports without wood samples; they will be included in a separate paper.

In hardwoods, we identified 17 cerambycid and one buprestid species, and at least seven additional cerambycids and two buprestids classified to genus level only (Supp Table 1 [online only]). In softwoods, we identified 27 cerambycid, six buprestid, and two siricid species, and at least eight additional cerambycids, three buprestids, and one siricid classified to genus only (the exact number of species could not be determined when multiple specimens were identified only to genus). The highest numbers and diversities of wood borers were found in *Pinus*, *Picea*, and *Populus*, in that order (Supp Table 1 [online only]). *Pinus* hosted 25 species, at least six additional species classified to genus only, and 118 specimens of cerambycids and buprestids identified to family level only. *Picea* hosted 20 species, at least eight species classified to genus only, and 48 unidentified members of Cerambycidae, Buprestidae, and Siricidae. *Populus* hosted eight species, one identified to genus only, and eight unidentified cerambycids. *Arhopalus rusticus* (Linnaeus) (Coleoptera: Cerambycidae), *Cephalallus unicolor* (Gahan) (Coleoptera: Cerambycidae), and *Trichoferus campestris* (Faldermann) (Coleoptera: Cerambycidae) were intercepted in both hardwoods and softwoods.

Among the identified insect species, most of the hardwood feeders are reported as polyphagous, while the softwood-feeding species are mostly oligophagous (Supp Table 1 [online only]). Hardwood WPM contained 19 species of polyphagous wood borers, whereas softwood WPM contained five purportedly monophagous species, 23 oligophagous (or possibly oligophagous) species, and seven polyphagous species. Several reportedly polyphagous species were indeed found in wood packaging belonging to more than one plant family; they included the cerambycids *A. rusticus*, *T. campestris*, *Xylotrechus magnicollis* (Fairmaire), *X. rufilus* Bates, and *X. smei* (Castelnau & Gory), and the buprestid *Belionota prasina* (Thunberg). *Trichoferus campestris* was found in wood belonging to four plant families: Betulaceae, Fagaceae, Pinaceae, and Salicaceae. The highly polyphagous cerambycid *Anoplophora glabripennis* Motschulsky (Coleoptera: Cerambycidae) (Lim et al. 2014, van der Gaag and Loomis 2014) was intercepted six times in *Populus* originating from a single wood-treatment facility in China, and once from India in *Mangifera* wood (but see the discussion on the provisional status of this record). Broader than expected diet breadth was discovered in three cerambycid and one buprestid species. *Arhopalus montanus*, reportedly monophagous on *Pinus* species (Linsley et al. 1961, Furniss and Carolin 1977), *Cephalocrius* (=*Arhopalus*) *syriacus* (Reitter) (Coleoptera: Cerambycidae), and *Pogonocherus perroudi* Mulsant (Coleoptera: Cerambycidae), also reportedly monophagous on *Pinus* (Brelih et al. 2006), were intercepted in both *Pinus* and *Picea* wood. The reportedly monophagous buprestid *Buprestis dalmatina* Mannerheim was also found in *Picea* in addition to its known *Pinus* host (Niehuis 1990, Lorubio et al. 2018). *Asemum caseyi* Linsley (Linsley 1957), a reportedly monophagous cerambycid, was intercepted with an identifiable wood sample only once, in its expected *Pinus* host genus (Supp Table 1 [online only]).

Potential Pest Status in the United States

The majority of intercepted wood borers identified to species were reported as pests in at least some part of their native or introduced ranges (Supp Table 2 [online only]). Some have the capacity to vector plant pathogens to coniferous trees: species of exotic and native cerambycids in the genus *Monochamus* [and possibly *Acanthocinus aedilis* (Linnaeus) [Coleoptera: Cerambycidae] (Jurc et al. 2012)] vector the plant-pathogenic nematode, *Bursaphelenchus xylophilus* (Steiner and Buhrer) Nickle (Aphelenchida: Parasitaphelenchidae). The woodwasps *Sirex juvencus* (Linnaeus) (Hymenoptera: Siricidae) and *Urocerus gigas gigas* (Linnaeus) (Hymenoptera: Siricidae) vector their symbiotic *Amylostereum* Boidin (Russulales: Amylostereaceae) wood-decay fungi. A cerambycid, *Tetropium castaneum* Linnaeus, can vector ophiostomatoid fungi (Jankowiak and Kolarik 2010). None of the 17 wood borer species intercepted in hardwoods are native to the United States, but three have reproducing populations there: *An. glabripennis* (Kappel et al. 2017), *Phoracantha recurva* Newman (Coleoptera: Cerambycidae) (Bybee et al. 2004), and *T. campestris* (Ray et al. 2019). Siricids were not intercepted in hardwood WPM. Among the non-native wood-boring species inhabiting softwoods, four cerambycids have become established in the United States, including *T. campestris* (Ray et al. 2019; also in hardwoods), *Tetropium castaneum* (LaBonte et al. 2005), *Callidium violaceum* (Linnaeus), and *Hylotrupes bajulus* (Linnaeus). The latter two are economic pests throughout their ranges and have been in North America for decades (Duffy 1953), *T. castaneum* is a pest in Europe (Evans et al. 2004), and the pest status of *T. campestris* is under investigation (B. Wang, USDA APHIS, personal communication). To our knowledge, none of the non-native buprestids and siricids intercepted in softwood WPM are established in the United States (Schiff et al. 2012).

Nineteen of the wood borer species, especially cerambycids and buprestids, apparently develop in living and lightly stressed hosts (LH; Group A pests), but many wood borers, including the siricid woodwasps, develop in declining and dead hosts (SH, DH, and DW; Group B pests). Available information indicates that about 10 beetle species intercepted in the present study appear to prefer dead to dry or decaying host wood (DH and/or DW; Supp Table 2 [online only]). Of the 35 identified insect species in softwoods, 8 (23%) were classed in Group A, 17 (49%) were classed in Group B or possible Group B, 9 (26%) were native in some parts of the United States, and we found no information for two additional species. Of the 17 insects identified to species in hardwoods, nine (53%) were classed in Group A, eight (47%) were classed in group B, and none were native in the United States. Two species were intercepted in both hardwood and softwood, one in Group A (*T. campestris*) and the other in Group B (*A. rusticus*; Supp Table 2 [online only]).

Phytosanitary Treatment Marks on Infested Wood

Most of the infested WPM had ISPM 15 marks indicating the wood was heat-treated rather than fumigated. Of the 480 interceptions with identified host wood, 416 (87%) had legible ISPM 15 marks with a treatment code; 317 softwood and 49 hardwood WPM items were marked as heat treated; and 16 softwood and 34 hardwood WPM items were marked as fumigated with methyl bromide. The remaining 64 samples had illegible marks, no treatment code, or lacked marks.

Discussion

This study revealed a diversity of packaging woods in which living cerambycid, buprestid, and siricid wood borers are transported to the United States through global trade, and provides the identities of

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many of the wood borer species carried within them. Although 36 host wood genera were identified, the majority (84%) of interceptions occurred in only three, *Pinus*, *Picea*, and *Populus*. These genera are known to be abundant in the WPM manufacturing industry (e.g., Bush and Araman 2009 for *Pinus* and *Picea*), but this study revealed their role as important hosts for diverse wood-boring insects in the WPM pathway. The majority of wood borer interceptions in these wood genera were associated with consignments originating from widely separated regions of the world: Mexico (*Pinus*), China (*Populus*), and Turkey (*Picea* and *Pinus*; Table 3), suggesting the risk associated with WPM is independent of geographic origin. Data collected in this study were, however, influenced by the frequency of WPM inspections aimed at certain commodity categories from these countries, mainly stone, metal, machinery, vehicles, and similar products.

Heavy products such as stone have been linked with higher WPM infestation rates (Haack 2006, Eyre and Haack 2017, Eyre et al. 2018). Assuming the commodities we grouped into stone, metal, machinery, and vehicle categories are considered heavy, our data support this trend (Tables 2 and 3). A prevalence of heavy-duty pallets associated with these commodities may contribute somewhat to higher observed infestations. Heavy-duty pallets are constructed of thicker wood than light-duty pallets (the weight-bearing threshold is approximately 660 kg; B. Gething, National Wooden Pallet and Container Association, personal communication), and greater wood volume per pallet may partly account for higher infestation rates of packaging associated with heavy commodities, while perhaps also increasing the likelihood of improper ISPM 15 treatment (Eyre and Haack 2017). Low-quality wood often used for heavy pallets has also been implicated (Eyre and Haack 2017), but is not yet empirically supported.

Lower-than-expected numbers of dunnage and crating wood samples were submitted to the study, but, in the case of dunnage, these were far lower than the reported number of interceptions. Wood specified as dunnage was intercepted 76 times, but only six samples were submitted, possibly due to the often large size of dunnage pieces, which would require greater effort and time than pallet wood to cut into samples. In contrast, although only seven infested WPM items were specified as crating, most of these samples were submitted.

Diverse wood borers, some already established pests in the United States and others with pest potential, were shown to be transported in WPM to U.S. ports (Supp Table 2 [online only]). A high proportion of these identified species are pests in their native areas, whereas some are also pests where they were accidentally introduced. It is possible that the species we were able to identify may be biased toward recognized pests because the growing popularity of molecular diagnostics may have led to better representation of DNA barcode sequences from pests than from benign species in the genetic databases. Two groups of non-native potential pests are recognized based on the condition of the hosts that they utilize: healthy or lightly stressed, and severely stressed to dead. Higher risk to horticultural crops, forests, and urban areas are posed by species that develop in living hosts (Group A, Supp Table 2 [online only]) rather than those that develop in severely weakened or dead hosts (Group B, Supp Table 2 [online only]; Evans et al. 2004). Among the identified species fitting this description are the Asian longhorned beetle, *An. glabripennis*, which lays its eggs and develops in living hardwoods over several generations as the trees decline, causing tree death (Hu et al. 2009, Haack et al. 2010); the Australian *P. recurva*, which lays eggs primarily in living eucalypts when outside its native range (Hanks et al. 1997); the *Monochamus* species, which can vector pinewood nematode (*B. xylophilus*) among conifers, especially pines (Dwinell and Nickle 1989); *Aromia moschata* (Linnaeus) (Coleoptera: Cerambycidae), which develops in living and weakened hosts (Hanks 1999); *Chlorida festiva* (Linnaeus) (Coleoptera: Cerambycidae), native from southeastern United States to Argentina and reported to kill mango trees in Brazil (Silva et al. 2016); *Tetropium castaneum*, an important secondary pest of softwood trees that vectors decay fungi (Evans et al. 2004), and *Callidium coriaceum* Paykull (Coleoptera: Cerambycidae), which is variously reported both as an important pest causing death of *Picea abies* (Linnaeus) H. Karsten in Fennoscandia (Lännenpää et al. 2008) and Poland (Gutowski 1983), and as attacking only severely stressed and dying *Picea* species (Pfeffer 1932, Juutinen 1960). Species that feed as larvae on stressed or dead hosts, or dry wood (Group B, Supp Table 2 [online only]), are potential lumber pests if introduced, and are reported to belong in all three host-breadth categories. Their suitable habitats extend not only to natural and planted forests but also to harvested timber, lumber, firewood, and wooden structures. *Hylotrupes bajulus*, the old-house borer, and *Callidium violaceum* are additional examples of intercepted species already present in North America. Potential new pests that could damage wood in stressed or dead trees include several *Xylotrechus* species, *Arhopalus ferus* (Mulsant), which can require quarantine treatment of log exports from New Zealand (Lawson et al. 2018), *Sirex juvencus* and *Urocerus gigas gigas*, which infect stressed conifers with decay fungi, promoting white rot and death (Talbot 1977).

The debarking rule for WPM was prompted by the requirement of most cerambycids, buprestids, and bark beetles for bark throughout much or all of their larval developmental period, without which they cannot complete development (Haack 2017). Some species require bark only in the early stages of larval development and lose the need as they later penetrate into the wood (Haack 2017). Several of the intercepted species fit this category, e.g., *B. prasina* (Ramasamy 2018) and *P. recurva* (Bybee et al. 2004). In these cases, the infested WPM might have originated from infested logs left in the forest or plantations for a sufficiently long time to allow larvae to penetrate the sapwood. Open storage of infested cants with bark prior to milling is another reason WPM may become infested before it arrives at the wood treatment facility (Haack and Petrice 2009). The woodwasp *Urocerus gigas gigas* is listed as an occasional pest in stored wood in Chile (Kline Koch and Waterhouse 2000).

About half the species intercepted in hardwoods (e.g., *An. glabripennis*, *P. recurva*) appear to require bark during their early developmental stages and are also polyphagous and known to infest healthy hosts (Group A pests; Bybee et al. 2004, Meng et al. 2015). Some of the softwood-inhabiting species [e.g., *Acanthocinus griseus* (Fabricius)] also require bark, but are not known to infest living trees, instead utilizing dead or decaying hosts (Martikainen 2002). In contrast with the hardwood borers, only 23% were classified in Group A and about half were classed in Group B, while several species were native (Supp Table 2 [online only]). Although the data are limited, it is interesting to note that hardwood packaging harbored a greater proportion of Group A pests than softwood packaging and that none of the identified hardwood borers are native in the United States (Supp Table 2 [online only]). We cannot conclude whether hardwood packaging poses greater pest risk than softwood packaging in general. The lack of native U.S. hardwood borers among the samples can be explained, however. Most native insect species arrived from Mexico, as expected, because it shares fauna and flora with the United States, but only softwood packaging samples were submitted from shipments originating in Mexico (Table 3).

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We remark that many of the collected insects that were submitted with and without wood samples have not yet been identified and could include important pests, and that our survey probably covered only a fraction of potential wood borer species in WPM.

Biological traits of other wood borers identified in this study suggest that they could have infested WPM post-treatment due to its improper storage in the open (Haack et al. 2014). Although cerambycids generally require at least some bark for oviposition and early larval development (Haack and Petrice 2009), a few species are capable of ovipositing and completing development in dry, barkless lumber, e.g., *Hylotrupes bajulus*, *Stromatium barbatum* (Fabricius), and *Stromatium longicorne* (Newman; Duffy 1953). We identified 12 *H. bajulus* specimens from six separate interceptions; all except two were reared to adult in the wood samples sent from the ports (two larvae had been damaged during inspection and were preserved). Two interceptions of *S. longicorne* were made, both bearing the ISPM 15 mark from a single WPM manufacturing and/or treatment facility in China. Although new pallets are generally constructed shortly before they enter the transport stream, some pallets are recycled and may be stored in the open (B. Gething, National Wooden Pallet and Container Association, personal communication); recycled pallets that require no repair also require no retreatment (IPPC 2018). Although dry, they are susceptible to occasional infestation by dry-wood borers (Haack and Petrice 2009).

A possible new host association is reported for the polyphagous cerambycid *An. glabripennis* on *Mangifera* sp. (Sapindales: Anacardiaceae). If confirmed, this association would represent a new host plant family record in the Anacardiaceae (see van der Gaag and Loomis 2014 for a review of known hosts). Some potentially confounding factors must be evaluated before the validity of this record can be firmly established. *Mangifera* is tropical and subtropical in distribution, whereas *An. glabripennis* generally requires cooler temperatures to develop and reproduce (Keena 2006); however, the ranges of the beetle and cultivated mango overlap in parts of southern China. For example, *An. glabripennis* has been collected in Yunnan Province (Javal et al. 2019), where *Mangifera indica* (mango) is cultivated. The latitude of *An. glabripennis* distribution in China has also been reported from 43°N as far south as the subtropics at 21°N (Yan 1985). A second confounding factor is that the pallet in which the two *An. glabripennis* larvae were purportedly found arrived in the United States with a shipment from India and bore an IPPC mark from India. Although no population of *An. glabripennis* is recorded in India (CABI 2018a), the possibility exists that it occurs there. Also, a pallet with infested *Mangifera* wood may have been shipped with goods from China to India and the infested part was used to repair another pallet in India; when pallets are repaired, old IPPC marks are replaced by new marks from the facility where the pallet receives its latest ISPM 15 treatment (IPPC 2018), erasing the history of the wood's origin. A third confounding factor is that the beetle larvae had been extracted from their galleries at the port and arrived at the Otis Laboratory in cups of artificial diet, along with the separated wood sample. We therefore cannot be certain that the larvae were removed from the *Mangifera* wood, although the wood had galleries consistent with wood borer infestation. The host record can be resolved only by collection of *An. glabripennis* in *Mangifera* sp. trees or through host testing. Potentially new host associations are also reported for the cerambycids *A. montanus*, *Cephalocrius* (=*Arhopalus*) *syriacus*, and *Pogonocherus perroudi*, and for the buprestid *Buprestis dalmatina*, all on *Picea* wood. These host-insect associations were encountered in one, five, four, and three interceptions, respectively. We found no prior records of these *Pinus*-feeding wood borers utilizing *Picea* species as hosts. Also new was *Picea* as a host for *Clytus rhamni* (Germar) (Coleoptera: Cerambycidae). To our knowledge, this polyphagous hardwood-feeder has never been reported from softwoods. Other typically hardwood feeders are known to utilize softwoods as hosts (e.g., *T. campestris*). We encountered larvae of *C. rhamni* in two interceptions of *Picea* wood originating with shipments from Eastern Europe (Supp Table 1 [online only]). One of these larvae was reared to the adult stage, but the adult was deformed and could not be identified morphologically, while the second specimen was killed and preserved in the larval stage when the project was nearing completion; however, their barcode sequences were 100% identical to *C. rhamni* sequences in BOLD. We also found no prior records of the polyphagous cerambycid *Xylotrechus buqueti* (LaPorte & Gory) (Coleoptera: Cerambycidae) on *Quercus* (Fagales: Fagaceae), or of *Pothyne* species on *Eucalyptus* (Myrtales: Myrtaceae).

We assumed that the origin of the wood was usually the port at which the shipments originated because the ISPM 15 mark on most (97%) of these WPM matched the country of origin for the shipment. However, country codes in the ISPM 15 marks of 3% of shipments differed from the port of origin, indicating the WPM was recycled in a different country without requiring repair (IPPC 2018). These occurred generally between neighboring countries in the European Union, and the identified wood borer species are known to occur in both countries. Unexpected wood borer origins were discovered, however. One WPM sample, identified as *Pinus* and assumed to originate from Brazil (based on the ISPM 15 mark and the origin of shipment), was infested with a larva of *T. campestris*. This Asian cerambycid species is not recorded from Brazil or elsewhere in South or Central America (CABI 2018c). Likewise, *A. montanus*, a Nearctic species native to the United States, was intercepted from Turkey in *Picea*. These cases could indicate that the insects had either spread to Brazil or Turkey, respectively, or that pallets were recycled there after inadequate treatment in their original places of manufacture. *Arhopalus montanus* is not reported from Turkey (Özdíkmen 2017), however, and could have arrived in recycled WPM (the type was unspecified), but recent finds of another North American wood borer, *Agrilus bilineatus* (Weber) (Coleoptera: Buprestidae), in Turkey (Jendek 2016, Hızal and Arslangündoğdu 2018) suggest that undetected populations of *A. montanus* and other North American wood borers may also exist in Turkey. The Australian *P. recurva* also likely arrived in infested WPM from established populations outside its native range, in Brazil and Turkey. It has spread widely to five continents where its eucalypt hosts are planted, including North America (California), South America, Europe, and Oceania (CABI 2018b). During this survey, it was intercepted twice from Brazil and once from Turkey. Because *P. recurva* was recorded only once from Turkey (Özdíkmen 2017), its status there is uncertain, but its occurrence in countries surrounding the Mediterranean Sea (CABI 2018b) suggests that this species may also be established in Turkey and that the infested wood originated there. The arrival of *An. glabripennis* from India was discussed earlier.

The identity of infested wood genera in WPM provides an additional layer of information in the WPM pathway-risk scenario for commodities arriving at U.S. ports. Although the data resulted from nonrandom sampling at ports, the high frequency of infested *Populus*, *Pinus*, and *Picea* interceptions likely reflects the frequency of these genera in the WPM construction industry but may also indicate that trees in these genera harbor higher loads of wood borers compared with other host genera used as WPM. Determining which of these two possibilities is responsible for the observed prevalence of pests in these wood genera is worthy of study. Exotic bark beetles that have become established outside their native range utilize

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mostly *Pinus* and *Picea* as hosts (Haack 2001), lending support to the common usage of these host genera for WPM, and at least some role of these hosts in their spread. *Pinus*, *Picea*, and *Populus* are economical and readily available woods that are unlikely to be eliminated from the WPM manufacturing stream to reduce risk of wood borer transport. This reinforces the argument for improving compliance with ISPM 15 regulations in conjunction with enhancing surveillance for non-native species (Allen and Humble 2002). The fact that 87% of the interceptions had an ISPM mark indicates that risks for the presence of wood borers include attempted but insufficient treatment of WPM, counterfeit marks, and reinfestation of treated material. The risks posed by wood borer species and genera identified here range from no known threats to potentially causing decline and death of healthy hosts, and their identities, along with other reports of intercepted and reared wood borers from WPM (e.g., Allen and Humble 2002, Eyre and Haack 2017), are providing advance notice for exclusion, surveillance, and control of non-native pests at risk of entering the country.

Supplementary Data

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

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