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Wood borer detection rates on wood packaging materials entering the United States during different phases of ISPM 15 implementation and regulatory changes

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Wood packaging material (WPM) used in international trade, such as crating and pallets, is recognized as a high-risk pathway for the introduction of bark- and wood-infesting insects (borers). The International Standards for Phytosanitary Measures No. 15 (ISPM 15), which sets treatment requirements for WPM, was adopted in 2002. The United States (US) implemented ISPM 15 during 2005–2006. We used 2003–2020 AQIM (Agriculture Quarantine Inspection Monitoring, conducted by USDA APHIS) data, based on standard random sampling, to compare pre-ISPM 15 borer detection rates in WPM entering the US (2003–2004) to detection rates during 2005–2006 (implementation phase), 2007–2009 (post-ISPM 15 when bark was not regulated) and 2010–2020 (post-ISPM 15 when bark was regulated). We examined borer detection rates overall for all AQIM WPM records and individually for the three main cargo survey programs within AQIM [Italian tiles, perishables, and general WPM (GWPM) for any WPM associated with containerized maritime imports], and individually for three major US trading partners (China, Italy, and Mexico). During 2003–2020, wood borers were detected in 180 of 87,571 consignments with WPM (0.21%). When compared to 2003–2004 (detection rate of 0.34%), detection rates fell 61% during 2005–2006, 47% during 2007–2009, and 36% during 2010–2020. Similar declines occurred for WPM associated with Italian tiles and perishables. However, for GWPM there was no significant reduction post-ISPM 15. WPM infestation rates were reduced significantly during various post-ISPM 15 periods for Italy and Mexico, but not for China. Seven families or subfamilies of borers were recorded in

WPM with Cerambycidae and Scolytinae being most frequent. The incidence of WPM with bark fell significantly after the 2009 change to ISPM 15 that required debarked WPM. We discuss several factors that could influence the apparent effectiveness of ISPM 15.

KEYWORDS

ISPM 15, wood packaging material, inspection, bark beetles, wood borers, detection, infestation

Introduction

As globalization and international trade have increased over the past century there has been a concomitant growth in containerization of traded goods, diversity of traded products, and speed of transport (Meurisse et al., 2019; Rodrigue, 2020). Associated with this increase in world trade has been an exponential increase in the arrival rate of non-native pests, several of which have severely impacted local ecosystems and economies (Kenis et al., 2009; Bradshaw et al., 2016; Brockerhoff and Liebhold, 2017; Seebens et al., 2017).

Freight is moved internationally by sea, air, and land, with maritime transport accounting for about 80% of the current total volume and air transport less than 1% (Rodrigue, 2020; United Nations Conference on Trade and Development [UNCTAD], 2021). Most non-bulk, dry freight (see definition below) is transported in containers; containerization increased from 23% in 1980, to 70% in 2000, and 85% in 2015 (Rodrigue, 2020). The standard metal containers used in maritime, truck and rail transport—quantified in terms of TEU (Twenty-foot Equivalent Units)—are either 20 ft (6.1 m = 1 TEU) or 40 ft (12.2 m = 2 TEU) long. Containerized cargo represented about 13% of all maritime trade volume in 2020, with the two largest maritime categories being liquid bulk (e.g., petroleum, vegetable oils; 35%) and dry bulk (e.g., coal, sand, grain; 40%) (United Nations Conference on Trade and Development [UNCTAD], 2021). Approximately 55 million TEU of containers entered the United States (US) in 2020, which is a 68% increase across the 2003–2020 period used in this study (World Bank, 2022). About 45% of containers entered at US maritime ports and 55% at land border crossings with Canada and Mexico (82% by truck and 18% by rail) (Customs and Border Protection [CBP], 2019). Air cargo utilizes lightweight containers of various sizes and designs (Rodrigue, 2020).

Wood packaging material (WPM) such as pallets, crating, and dunnage are commonly used to support, protect, and brace cargo within containers and vessels. Based on US imports during 2005–2007, WPM was present in about 75% of containerized maritime cargo and 33% of air cargo (Meissner et al., 2009). WPM can be manufactured from virtually any woody plant. For example, Krishnankutty et al. (2020) identified 36 different tree genera used for WPM from a sample of 480 infested pieces of WPM associated with US imports from 42 countries. *Pinus* (pine), *Picea* (spruce) and *Populus* (poplar) were the most frequent genera represented in those WPM samples.

Worldwide there are thousands of insect species that develop in the bark and wood of trees, which we will refer to as "wood borers" or "borers" in this paper. Worldwide, most of the 15,000 known beetle (Coleoptera) species in the family Buprestidae (flatheaded wood borers; Chamorro et al., 2015; Volkovitsh, 2020), and the vast majority of the 36,000 known Cerambycidae (roundheaded wood borers; Bílý, 1982; Nelson et al., 2008; Haack, 2017; Wang, 2017) are wood borers. Given that different species of borers may develop in living, dying, and recently dead or cut trees, as well as have larval development times that usually range from several months to a few years (Haack and Slansky, 1987; Hanks, 1999), borers will occasionally be associated with WPM. Many species of wood-boring Coleoptera, Hymenoptera, Isoptera, and Lepidoptera have been intercepted in WPM (Bain, 1977; Haack, 2001; Humble, 2010; Haack et al., 2014; Eyre et al., 2018; Lawson et al., 2018; Zhao et al., 2021). Although the exact mode of entry for most non-native wood borers when discovered in natural ecosystems outside their native range is usually unknown, WPM is often suspected. Some examples, which occurred before ISPM 15 implementation, include the establishment of the North American scolytine bark beetle *Ips grandicollis* in Australia (Morgan, 1967), the Eurasian siricid woodwasp *Sirex noctilio* in New Zealand and the US (Hoebeke et al., 2005; Burnip et al., 2010), the Asian cerambycid *Anoplophora glabripennis* in North America and Europe (Haack et al., 2010), and the Asian buprestid *Agrilus planipennis* in the US (Herms and McCullough, 2014).

In response to growing phytosanitary concerns with WPM, contracting parties of the International Plant Protection Convention (IPPC) adopted the International Standards for Phytosanitary Measures No. 15 (ISPM 15) in 2002, which described requirements for heat and fumigation treatments of WPM used in international trade (Allen et al., 2017; Food and Agriculture Organization [FAO], 2019). There were two treatment options in 2002: heat treatment using a conventional kiln (marked as HT) and fumigation using methyl bromide (MB). In recent years, dielectric heating (DH) and sulphuryl fluoride fumigation (SF) were added as acceptable treatment options (Food and Agriculture Organization [FAO], 2019). The goal of ISPM 15 is to significantly reduce the risk of pests, which can be associated with solid wood used for constructing most forms of WPM, from being introduced to other countries through international trade (Food and Agriculture Organization [FAO], 2019). ISPM 15 does not regulate processed wood products such as plywood, particle board, and oriented strand board, because they have a very low risk of being infested (Food and Agriculture Organization [FAO], 2019). Since 2002 there have been many changes to ISPM 15, with the most recent version published in 2019 (Food and Agriculture Organization [FAO], 2019). Important changes to ISPM 15 were approved in 2009 and included requirements for WPM to be made from debarked wood, size tolerance limits for any patches of residual bark (allowed patches <3 cm in width regardless of length, or >3 cm in width but <50 square cm in size), and debarking prior to fumigation. After WPM is treated to comply with ISPM 15, it is stamped in a specific way with the official IPPC mark, including a two-letter country code indicating where it was treated, a producer code to indicate the treatment provider, and a treatment code to specify how the WPM was treated (Food and Agriculture Organization [FAO], 2019).

After adoption of ISPM 15 in 2002, New Zealand was the first country to implement it, starting in 2003, followed by Australia in 2004, and the European Union in 2005. The US implemented ISPM 15 in phases over a 10-month period (September 2005–July 2006) (Haack et al., 2014). During that period, the US began enforcement of ISPM 15 on pallets and crating in February 2006, and on all WPM beginning on 5 July 2006. Many countries have now formally adopted ISPM 15, including all the major export markets worldwide (US Department of Agriculture Animal and Plant Health Inspection Service [USDA APHIS], 2020).

The US Department of Agriculture (USDA) Animal and Plant Health Inspection Service (APHIS) is the federal agency tasked with developing science-based regulations and issuance of permits that detail the requirements and conditions for safely importing agricultural products into the US. There are several types of inspection programs conducted at US ports. In the Agriculture Quarantine Inspection Monitoring (AQIM) program, APHIS monitors various pathways and commodities entering the US. Under AQIM, data are collected using random sampling of specific numbers of passengers and imported shipments (e.g., containers) within various survey categories at selected US maritime ports, airports, and land border crossings with Canada and Mexico (**Figure 1**). Both negative (where no pests are found) and positive (where pests are found) inspection results are recorded, which allows AQIM results to be used to estimate unbiased infestation rates for the various types of cargo and pathways. Although AQIM began in 1997, routine inspections of WPM first began in October 2003. Most ports involved in AQIM have remained the same since the program began. Currently there are 49 ports in the AQIM program where WPM is commonly encountered, including 21 maritime ports, 13 airports, 6 land crossings with Canada, and 9 land crossing with Mexico (**Figure 1**; US Department of Agriculture Animal and Plant Health Inspection Service [USDA APHIS], 2021). About 6,000 inspections of WPM are conducted annually at these 49 ports as part of AQIM. Note that the inspection effort within AQIM is very consistent from year to year and is generally not influenced by changes in trade volume.

The three main cargo survey programs in AQIM where WPM is frequently found include perishables (e.g., fruit, vegetables, cut flowers), Italian tiles, and general WPM associated with any maritime containerized product. To avoid confusion, we will use GWPM when referring to WPM inspected in the "general" WPM survey. All types of WPM (e.g., crating, pallets, and dunnage) are encountered in each survey program, although the percentages of each type vary by program. Commercial perishable plant cargo is the primary focus of AQIM inspections at airports and land border crossings, whereas all three cargo survey programs are conducted at maritime ports. APHIS has specific protocols for how samples are selected and inspected. For example, two 40-ft-long containers are randomly selected weekly at each participating maritime port for each survey program (US Department of Agriculture Animal and Plant Health Inspection Service [USDA APHIS], 2021). Some maritime ports participate in only one survey program, some two, and three ports participate in all three survey programs (i.e., Port Everglades, FL; Miami, FL; and Newark, NJ). It is important to note that AQIM does not survey WPM associated with breakbulk maritime cargo, where products are packaged and loaded individually without using containers.

During AQIM inspections, information is collected on a consignment basis by Agriculture Specialists working for US Customs and Border Protection. Therefore, when an actionable pest is found, the entire consignment is regulated based on the risk of the pest, regardless of the number of individual pests, individual commodity units, or WPM items in the same consignment. Several data fields are completed for each inspection, such as the date of inspection, US port-of-entry, if the inspection was part of a special survey program, country of origin and description of the imported commodity, type of WPM, if the WPM had the ISPM 15 mark, if bark was present on the WPM (although size of bark patches is not recorded), and if any pests were found. Pests are identified to various taxonomic levels, often depending on what defining characteristics can be observed on the life stages that are encountered. Generally, most insects are identified to the family level, with fewer identified to genus, and fewest to species (Haack et al., 2014). Further details on AQIM can be found in the AQIM Handbook (US Department of Agriculture Animal and Plant Health Inspection Service [USDA APHIS], 2021), with the statistical methods explained more fully in Venette et al. (2002). AQIM data have been used by other researchers to examine pest infestation rates

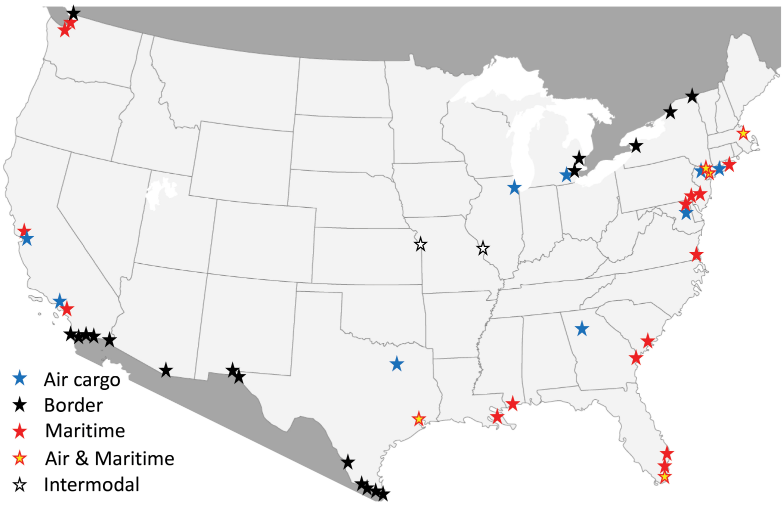

FIGURE 1
All ports in the contiguous 48 US states where WPM was inspected as part of the AQIM program during 2003–2020. Not shown are the participating ports of Honolulu, HI and San Juan, PR. Source of base map: freeworldmaps.net.

on various commodities (Work et al., 2005; Meissner et al., 2009; Liebhold et al., 2012; Haack et al., 2014).

In the earlier study by Haack et al. (2014), AQIM data were used to estimate wood borer infestation rates of WPM entering the US both before and after implementation of ISPM 15, using data through 2009. Depending on which countries were included and how the time periods were selected to separate pre- and post-ISPM 15, they reported a 36–52% reduction in the WPM infestation rate following ISPM 15 implementation; see **Supplementary Data Sheet 1** for a comparison of the methods used in the current study with those used in Haack et al. (2014). Although this downward trend was encouraging, borers have continued to be found in imported WPM in recent studies conducted in Australia (Lawson et al., 2018), China (Zhao et al., 2021), and Europe (Eyre et al., 2018). In the current analysis, using AQIM data from 2003 through 2020, our main objectives were to (1) compare pre- and post-ISPM 15 borer-infested WPM detection rates, and (2) calculate and compare the borer detection rates individually for the various survey programs within AQIM and key US trading partners. We also wanted to inspect the data for any seasonality of wood borer detections, as well as assess the diversity of borer taxa detected overall, and by cargo category and country of origin.

Materials and methods

Data and records classification

We obtained all AQIM records from October 2003 (when WPM was first inspected as part of AQIM) through 2020 where WPM was associated with the inspected consignments. This period included data from different phases of ISPM 15 as follows.

- Two years preceding implementation of ISPM 15 by the US: pre-ISPM 15 = 2003–2004.
- Two years during which ISPM 15 was initiated by the US: implementation = 2005–2006. During September 2005 to February 2006, brokers were notified of any ISPM 15 infractions. Full enforcement began on pallets and crating in February 2006, and on all WPM in July 2006. Residual bark was not regulated during this period.
- Three years when residual bark was not regulated on treated WPM; post-ISPM 15 with bark = 2007–2009, and
- Eleven years when the size of residual pieces of bark on treated WPM was regulated; post-ISPM 15 without bark = 2010–2020.

Therefore, the US regulations related to ISPM 15 were broadly consistent within each of these four phases. We analyzed the data in three separate ways: all cargo-related WPM records as a whole; separately for the three major survey programs (perishables, Italian tiles, and GWPM); and separately for three major US trading partners (China, Italy, and Mexico).

For those AQIM records with WPM where insects were detected, we first categorized each insect taxon as a likely bark- or wood-infesting insect or not. Some of the intercepted insects were agricultural pests and likely associated with the imported perishable cargo, while several others were considered hitchhikers that inadvertently contaminated the cargo or WPM. Classifying insects as wood borers was straightforward when they were identified to genus or species, based on life history descriptions available in the literature. Insects identified to only family or subfamily level were classified as likely wood borers if they were in the beetle (Coleoptera) families Buprestidae or Cerambycidae, or the weevil (Curculionidae) subfamilies Platypodinae or Scolytinae (bark and ambrosia beetles). Similarly, records of carpenterworms (Lepidoptera: Cossidae) and woodwasps (Hymenoptera: Siricidae) were classified as likely wood borers. Weevils (Curculionidae) in the subfamily Cossoninae were also classified as wood borers when the beetles were associated with WPM, because many Cossoninae species are true wood borers (Jordal et al., 2011). However, we did not classify the few records of wood-infesting insects identified as Bostrichidae (powderpost beetles) or Isoptera (termites) as borers because these insects can infest WPM after treatment and therefore cannot be used to judge the effectiveness of ISPM 15 (Haack et al., 2014). When more than one species of wood borer was found in the same consignment, all taxa were recorded, but the individual consignment was simply considered infested regardless of the number of distinct borer species found.

Analysis

Prior to analysis, we excluded all Canadian records because the US did not require Canadian WPM to meet ISPM 15 standards during the sampling period, given that the vast majority of bark- and wood-infesting insects native to Canada also occur in the US (Bright, 1976, 1987, 2021; Bousquet et al., 2017). In addition, for the period 2006–2020, we only included those records where the WPM had the ISPM 15 mark, indicating that the WPM was apparently treated to ISPM 15 standards. Note that most of the WPM inspected since 2006 has been marked with the ISPM 15 mark (**Figure 2**). We will refer to this reduced dataset as the "final dataset" used in the analyses below.

We separately tested the borer detection rate in WPM for 2003–2004 against the rates in the 2005–2006, 2007–2009, and 2010–2020 periods. We constructed 2 × 2 contingency tables for each comparison and analyzed each using Fisher's exact test (one-sided probability, PROC FREQ, SAS Institute, Cary, NC). We used a significance level of $\alpha = 0.1$ and did not correct for multiple comparisons because infestation rates of WPM are usually low and we wanted to reduce the likelihood of committing a Type II error (i.e., a false negative). The above procedure was used to examine borer detection rates for all WPM records overall, for the three main survey programs (perishables, Italian tiles, and GWPM), and for the three major US trading partners (China, Italy, and Mexico). We also conducted chi-squared tests (PROC FREQ, SAS Institute), and calculated running averages for certain categories and inspected them for long-term trends.

Results

Pathway summary

The AQIM database contained 109,709 inspection records with WPM from 2003 to 2020. These records represented consignments from 172 countries, with the top 15 countries being Mexico (30.4% of all records), Canada (18.2%), Italy (12.7%), China (4.6%), Costa Rica (3.6%), Guatemala (2.7%), Netherlands (2.5%), Dominican Republic (2.4%), Brazil (2.1%), India (2.0%), Ecuador (1.6%), Honduras (1.5%), Turkey (1.4%), Spain (1.4%), and Germany (1.4%). The number of countries from which WPM originated increased during each period, and more than doubled from 2003–2004 to 2010–2020 (**Table 1**), although annual numbers of countries with wood borer detections have dropped since 2018 (**Figure 3**). Note that when data are expressed on an annual basis, 2003 only contains data for 3 months (October-December), given that AQIM first started recording WPM data in October 2003.

For the entire 2003–2020 dataset, 88.6% of the inspected WPM items were recorded as pallets, 7.5% as crating, 2.4% as dunnage, and 1.4% as other (e.g., wood blocks and spools; **Figure 4**). These four types of WPM were encountered in each of the three main survey programs during 2003–2020. For the GWPM program, the WPM types were 64.7% pallets, 23.1% crating, 8.2% dunnage, and 4.0% other. For perishables the WPM types were 98.5% pallets, 1.2% crating, 0.1% dunnage, and 0.2% other. For Italian tiles the WPM types were 92.0% pallets, 5.9% crating, 1.1% dunnage, and 1.0% other.

The final dataset used for analysis had 87,571 records after removal of all consignments from Canada, as well as those records with unmarked WPM during the years 2006–2020. As an aside, no borers were detected in any of the Canadian WPM records that were excluded.

Wood borers were detected in 180 of the 87,571 consignments with WPM (0.21%). Of these detection records, 67.2% were in pallets, 29.4% were in crating, 2.2% were in dunnage, and 1.1% were classified as other (**Figure 4**). When expressed as borer detection rates, wood pests were detected significantly more often on crating (0.64%) than pallets (0.12%), dunnage (0.15%), or other (0.13%) ($\chi^2 = 124.1$, $P < 0.0001$). The 180 infested consignments originated from 30 countries, with 10 from Europe (including Russia), 8 from Asia (including Turkey), 6 from South America, and 5 from both Central America and Mexico (**Table 1**). The number of countries from which infested WPM originated generally increased over time (**Table 1** and **Figure 3**). During the 2003–2020 period, borers were detected in WPM in eight or more years for only five countries (**Figure 5**), which also were the countries with the most borer detections: China (40), Italy (27), Mexico (22), Costa Rica (18), and Turkey (15) (**Table 1**). Consignments with infested WPM were detected in all months of the year, showing no strong seasonal interception pattern (**Figure 6**).

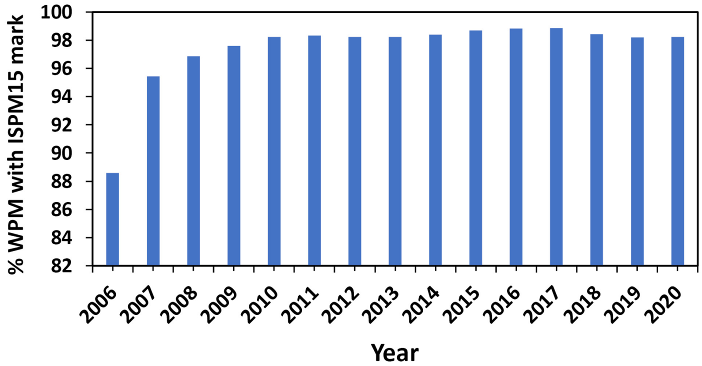

FIGURE 2
Percentage of AQIM records with WPM during 2006–2020 where the WPM was recorded as being stamped with the ISPM 15 mark.

TABLE 1 Summary data for the number of AQIM records where WPM was infested with wood borers and their countries of origin during four time periods from 2003 to 2020, based on the final dataset (see section "Materials and methods").

Parameter	Time period				
	2003–2004	2005–2006	2007–2009	2010–2020	
Borer-infested consignments with (no.)	12	13	31	124	
Consignments with multiple borer families (no.)	0	0	2	4	
Borer families* (no.)	2	3	3	7	
Countries with borer detections (no.)	5	9	12	25	
Total countries with inspected WPM (no.)	75	109	119	154	
Countries with live wood borer detections in WPM in decreasing order (*N* = number of consignments with infested WPM)	Italy (4) Mexico (4) China (2) Nicaragua (1) Russia (1)	Mexico (4) China (2) Costa Rica (1) Greece (1) Poland (1) Portugal (1) Spain (1) Turkey (1) Venezuela (1)	China (11) Mexico (5) Turkey (4) Italy (3) Argentina (1) Brazil (1) Colombia (1) Guatemala (1) Philippines (1) Poland (1) South Korea (1) Vietnam (1)	China (25) Italy (20) Costa Rica (17) Turkey (10) Mexico (9) Brazil (5) Spain (5) Guatemala (4) Ecuador (3) Greece (3) India (3) Indonesia (3) Nicaragua (3)	Honduras (2) Poland (2) Belgium (1) Bulgaria (1) Colombia (1) El Salvador (1) Netherlands (1) Peru (1) Portugal (1) Slovakia (1) Syria (1) Vietnam (1)

*Platypodinae and Scolytinae were treated as separate families from the other Curculionidae.

The AQIM data showed that WPM was associated with several hundred different types of commodities. The top five perishable imports with WPM were (decreasing order) broccoli, pineapples, tomatoes, bananas, and peppers. The top five non-perishable imports with WPM were (decreasing order) tiles, auto parts, stone slabs, machinery, and metal. The most common commodities with infested WPM followed these same trends (Table 2 and Supplementary Table 1).

Taxonomic diversity of wood borers

The infested consignments contained seven families or subfamilies of wood borers (with all seven being referred to as families for simplicity): five families of Coleoptera (Buprestidae, Cerambycidae, Platypodinae, Scolytinae, and other Curculionidae), plus Siricidae and Cossidae (Tables 2, 3). Five of the 180 infested consignments had borers from two different families and one consignment had borers from three families, and therefore when organized by borer family they represented 187 borer-consignment combinations (Tables 2, 3). Cerambycidae were the most commonly intercepted borers overall (93 of 187, or 49.7%), with Scolytinae being the second most frequent (39.0%) (Table 3). The diversity of wood borers found in WPM increased over time, with the Cerambycidae and Scolytinae consistently being the two most common borer families intercepted during each of the four time periods (Table 3). The 3-year running average for the

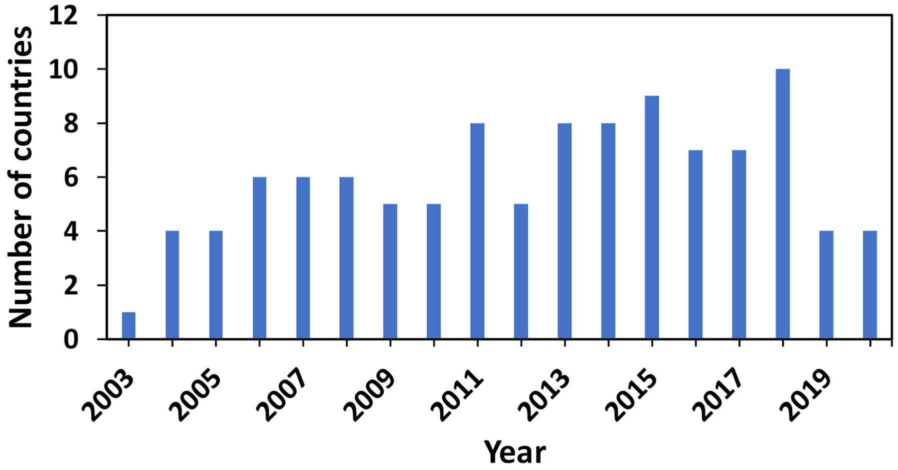

FIGURE 3
Number of countries of origin from which wood borers were detected in WPM imported into the US by year from 2003 to 2020.

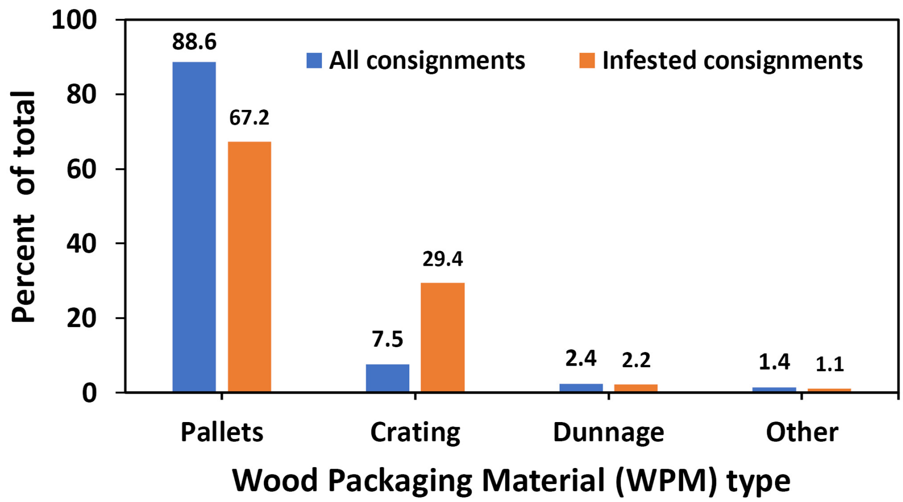

FIGURE 4
Percentage of all consignments with WPM in the final dataset by the type of WPM inspected (*N* = 87,571), and percentage of all 180 consignments in which wood borers were found by WPM type. Other refers to WPM items such as wood blocks and spools.

mean annual number of detections for the four most intercepted beetle families indicated that cerambycid interceptions were consistently high, scolytine interceptions were the next most frequent and surpassed the cerambycid detections in the 2010s for a few years, and both buprestid and platypodine interceptions remained low but peaked in the mid-2010s (Figure 7). Most of the wood borer families recorded in this study were found in crating and pallets (Table 3). The most common genera of wood borers of those identified to genus or species are listed in Table 2. For the Scolytinae that were identified to genus or species (45% of 73 interceptions), 100% were true bark beetles (which develop primarily under bark) during 2003–2004 and 2005–2006, but only 40% in 2007–2009, and 23% in 2010–2020, with the others being ambrosia beetles (which develop inside wood) (Supplementary Table 1).

Wood packaging material characteristics

The presence of bark on WPM was recorded in nearly all the original AQIM records from 2003 to 2020, although patch size of any residual bark was not recorded (*N* = 109,707). The percentage of WPM consignments with bark was 3.4% in 2003–2004, 2.6% in 2005–2006, 2.3% in 2007–2009, and 1.2% in

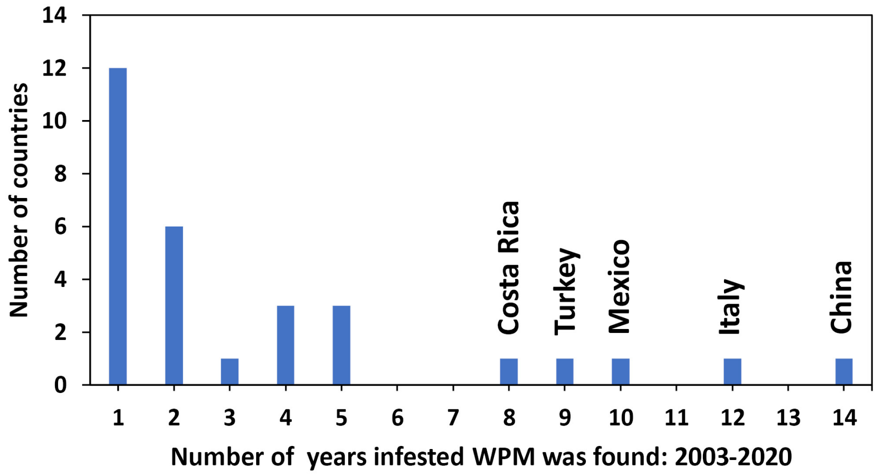

FIGURE 5
Number of countries of origin from which wood borers were detected in WPM imported into the US by the number of years that borers were detected from individual countries during the period 2003–2020.

2010–2020. When compared to 2003–2004, each of the later three periods had significantly reduced percentages of WPM with bark (Fisher's exact test $P = 0.007$ for 2005–2006; $P < 0.0001$ for both 2007–2009 and 2010–2020). Similarly, the 46% decrease in the percentage of WPM with bark from 2007–2009 to 2010–2020 was significant (Fisher's exact test $P < 0.0001$).

Overall, bark was present in 22.5% of the 180 wood borer detections in WPM. By period, bark was present on 40% of detections in 2003–2004, 46% in 2005–2006, 39% in 2007–2009 records, and 15% in 2010–2020, demonstrating a significant decline for the last period (Fisher's exact test $P = 0.004$). Unfortunately, AQIM data do not indicate if the detected borers were found under bark (if present) or in the wood, but simply that bark was present somewhere on the WPM.

The presence of the official ISPM 15 mark on WPM was first recorded in the AQIM database in October 2005. Overall, 72% of the WPM inspected during October-December 2005 was marked. The percentage of marked WPM entering the US increased to 89% in 2006 and 95–99% was marked during 2007–2020 (Figure 2).

Wood packaging material infestation rates by period

Within the three AQIM survey programs, the overall detection rate of borer-infested WPM entering the US immediately before ISPM 15 implementation (2003–2004) was 0.34% (Table 4). Rates were significantly lower ($P < 0.1$) in two subsequent periods: 0.13% during 2005–2006 (61% reduction compared to 2003–2004, $P = 0.017$), and 0.18% during 2007–2009 (47% reduction, $P = 0.054$). The 2010–2020 rate of 0.22% (36% reduction) was also lower, and nearly significant ($P = 0.102$). The overall infestation rate of WPM at 2-year intervals also indicated a sharp drop during 2005–2006 and a temporary rise in infested WPM during the mid-2010s (compare the "Total" bars in Figure 8).

Detection rates of borer-infested wood packaging material over time by survey program

Wood borer detection rates were greatest for the GWPM program (Table 4 and Figure 9), and cerambycids were the most common borers associated with infested GWPM (66% of detections; Supplementary Table 1). We found no significant differences in detection rates by period, which ranged from 0.33% during 2005–2006 ($P = 0.486$) to 0.41% during 2007–2009 ($P = 0.603$) (Table 4). In fact, when viewed at 2-year intervals, borer detection rates of GWPM were rather consistent over time (Figures 8, 9). Of all inspections classified as GWPM, most originated from China (18.4%), with the next five highest countries of origin being (decreasing order) India, Brazil, Germany, Italy, and Turkey.

For the Italian tiles program, wood borer detection rates in WPM declined by almost two thirds from 2003–2004 (0.62%) to 2010–2020 (0.23%) and was near zero during much of 2005–2009 (Table 4 and Figures 8, 9). When compared to the 2003–2004 detection rate, these reductions were significant during the 2005–2006 ($P = 0.020$) and 2007–2009 ($P = 0.018$) periods, but not the 2010–2020 period ($P = 0.127$; Table 4). Wood borer detection rates on Italian tiles spiked from 2015 to 2018 for unknown reasons, but never exceeded 0.1% (Figure 8). As expected, 99.8% of all consignments recorded as Italian tiles originated from Italy. Most detections in

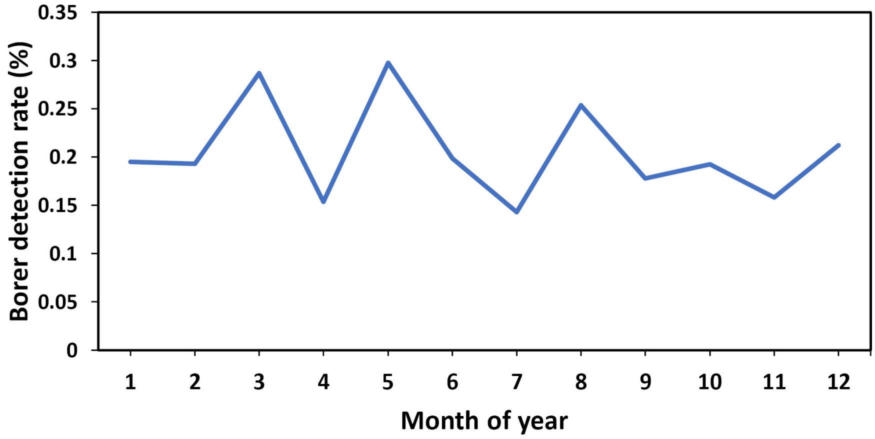

FIGURE 6
Percentage of AQIM records with WPM in which borers were detected by month of year for inspections conducted at US ports during 2003–2020.

TABLE 2 Summary data for the wood borers reported in WPM in the AQIM program 2003–2020 by insect family or subfamily, based on the final dataset.

Order	Family or subfamily	Top 3 genera*	Records (no.)	Ports (no.)	States (no.)**	Countries (no.)	Top countries	Most common commodities
Coleoptera*	Buprestidae	None	8	6	4	5	Italy, Turkey	Tiles, stone
	Cerambycidae	*Arhopalus, Monochamus, Tetropium*	93	20	15	23	China, Italy, Turkey	Tiles, stone, machinery
	Curculionidae	Only Cossoninae	1	1	1	1	Italy	Tiles
	Platypodinae	*Platypus*	7	4	3	5	China, Costa Rica, Colombia	Perishables, tiles
	Scolytinae	*Xyleborus, Pityophthorus, Ips*	73	23	15	18	Mexico, Costa Rica, Italy	Perishables, tiles, stone
Hymenoptera	Siricidae	*Urocerus*	3	2	2	2	China, Greece	Stone
Lepidoptera	Cossidae	*Langsdorfia*	2	2	1	2	China, Guatemala	Metal

*Platypodinae and Scolytinae treated separate from Curculionidae. **Puerto Rico was treated as a US state in this Table, with three wood borer records in WPM made at the maritime port of San Juan, PR (1 cerambycid, 1 platypodine, and 1 scolytine).

TABLE 3 Summary data for the wood borers intercepted in WPM at US ports during four time periods from 2003 to 2020, based on the final dataset.

Order	Family	No. records	WPM type**	Percent of interceptions per period				
				2003–2004	2005–2006	2007–2009	2010–2020	2003–2020
Coleoptera	Buprestidae	8	C, P	0	0	0	6.2	4.3
	Cerambycidae	93	C, D, P	58.3	46.2	57.6	47.3	49.7
	Curculionidae	1	P	0	0	0	0.8	0.5
	Platypodinae*	7	C, P	0	0	3.0	4.7	3.7
	Scolytinae*	73	C, D, P	41. 7	46.2	39.4	38.0	39.0
Hymenoptera	Siricidae	3	C, O, P	0	0	0	2.3	1.6
Lepidoptera	Cossidae	2	C, P	0	7.7	0	0.8	1.1
Total records		187		12	13	33	129	187

*Platypodinae and Scolytinae treated separately from Curculionidae. **WPM types: C = crating, D = dunnage, O = other (e.g., blocks and spools), and P = pallets.

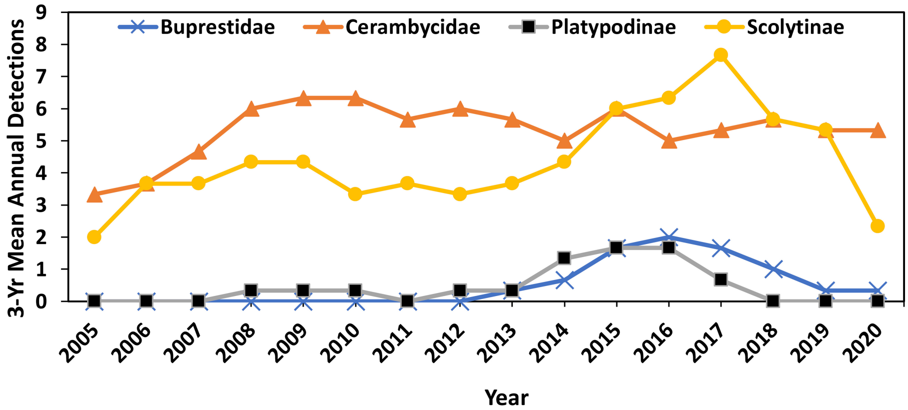

FIGURE 7
Three-year running averages for the four main groups of wood borers intercepted in WPM during 2003–2020 based on the final dataset for AQIM records from 2003 to 2020.

TABLE 4 Detection rates (%) of borer-infested WPM inspected as part of the AQIM program during four time periods from 2003 through 2020 that bracket when the US implemented ISPM 15 in 2005–2006.

Survey program	Period	No. inspections	No. wood borer detections	Detection rate (%)	% Reduction (*P*-value)
All WPM	2003–2004	3,549	12	0.34	–
	2005–2006	9,869	13	0.13	61.0 ($P = 0.017$)
	2007–2009	17,125	31	0.18	46.5 ($P = 0.054$)
	2010–2020	57,028	124	0.22	35.8 ($P = 0.102$)
Italian tiles	2003–2004	488	3	0.62	–
	2005–2006	1,307	0	0.0	100 ($P = 0.020$)
	2007–2009	2,322	1	0.04	93.0 ($P = 0.018$)
	2010–2020	7,677	18	0.23	62.0 ($P = 0.127$)
Perishables	2003–2004	1,969	4	0.20	–
	2005–2006	5,844	4	0.07	66.5 ($P = 0.117$)
	2007–2009	9,476	6	0.06	69.0 ($P = 0.077$)
	2010–2020	30,578	38	0.12	38.9 ($P = 0.248$)
GWPM	2003–2004	1,003	4	0.40	–
	2005–2006	2,419	8	0.33	17.0 ($P = 0.486$)
	2007–2009	4,647	19	0.41	+2.5 ($P = 0.603$)
	2010–2020	18,592	68	0.37	8.3 ($P = 0.507$)

Data are presented first for all AQIM inspections where WPM was recorded as well as for three survey programs within AQIM (Italian tiles, Perishables, and GWPM, the latter which targeted primarily WPM associated with containerized maritime cargo). Within each category, detection rates for the three periods from 2005 to 2020 were compared individually to the pre-ISPM 15 period (2003–2004) with a one-sided Fisher's exact test (alpha = 0.1). Analyses were conducted on the final dataset.

this survey program were cerambycids (68%; Supplementary Table 1).

For the perishable goods program, wood borer detection rates declined overall from 0.20% in 2003–2004, to 0.06–0.07% during 2005–2006 and 2007–2009 (∼70% reduction), and to 0.12% during 2010–2020 (39% reduction, Table 4 and Figure 9). These reductions were only significant for the period of 2007–2009 ($P = 0.077$, Table 4). When viewed at 2-year intervals, detection rates in WPM associated with perishables decreased at first and then increased again during 2009–2018, peaking during 2013 (Figure 8). Overall, 66.9% of all consignments of perishables with WPM originated from Mexico. The next five countries with the highest number of perishable records were (decreasing order) Costa Rica, Guatemala, Netherlands, Ecuador, and the Dominican Republic. Scolytines were the most frequent borers detected in WPM associated with perishables (77%; Supplementary Table 1).

Wood packaging material infestation rates over time by country

We found no significant reductions for wood borer detection rates in WPM from China during any post-ISPM 15

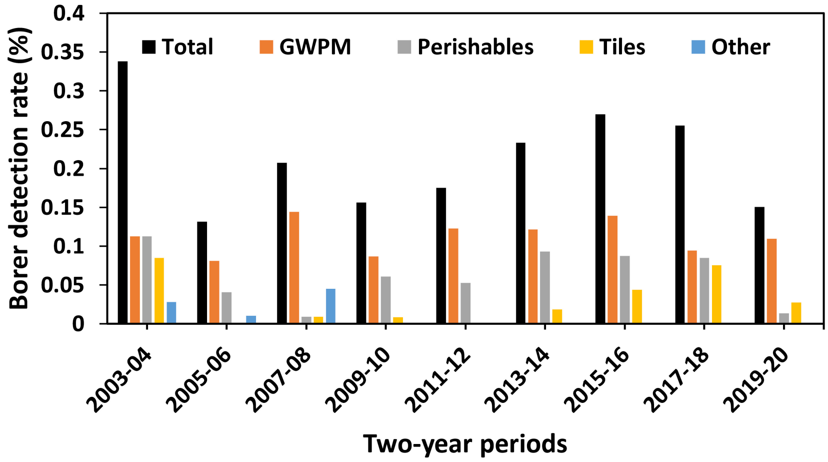

FIGURE 8
Detection rates for wood borers in WPM at US ports averaged over 2-year periods for AQIM final dataset 2003–2020 by selected AQIM survey programs (see section "Materials and methods") and for all survey programs combined (total).

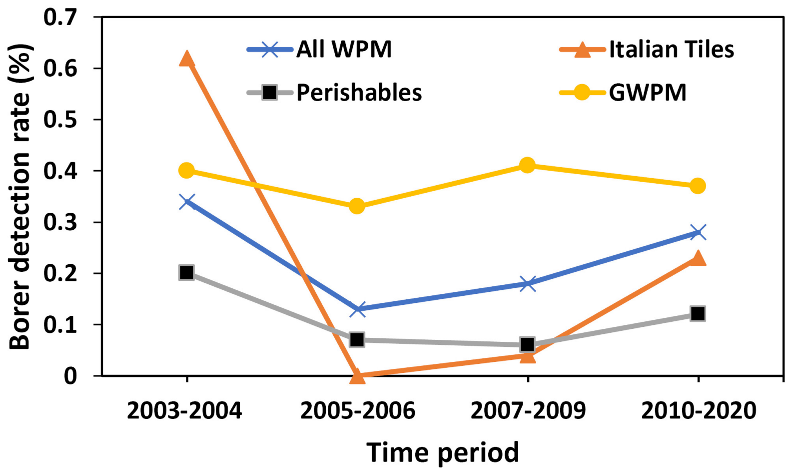

FIGURE 9
Detection rates (%) of borer-infested WPM inspected as part of the AQIM program during four time periods from 2003 through 2020 that bracket when the US implemented ISPM 15 in 2005–2006. Data are presented for all AQIM inspections where WPM was recorded as well as for three major survey programs within AQIM: Italian tiles, perishables, and GWPM (general survey of all types of WPM associated with containerized maritime cargo).

period (Table 5). The great majority of the detections for China appeared in the GWPM program (91.0%). For China, the WPM infestation rate was 1.26% during 2003–2004, and ranged from 0.58 to 1.11% during the next three periods (Table 5).

We did, however, find significant rate reductions for borer detections in WPM from Italy and Mexico (Table 5). For Italy, borer detection rates were significantly lower during each period compared to 2003–2004, although they lessened over time (Table 5). As expected, most wood borer detections in WPM from Italy were on Italian tiles (86.7%). Borer detection rates in WPM from Mexico continually declined over time, from a 64% reduction during 2005–2006, to an 85% reduction during 2010–2020 (Table 4). Nearly all borer detections from Mexico were on perishables (98.9%). Because detections of infested WPM for each of the above three countries were primarily associated with a single, distinct survey program, these three countries greatly influenced detection rates within the three survey programs listed in Table 4.

Costa Rica and Turkey ranked fourth and fifth overall for wood borer detections in WPM, with borer detection rates generally increasing over time for both countries. The borer detection rate for Costa Rica was 0.072% (1 of 1,382 consignments) during all of 2003–2009 but increased to 0.665% (17 of 2,555) during 2010–2020. Similarly, for Turkey, the borer detection rate was zero during 2003–2004 (0 of 59 consignments), 0.83% during 2005–2006 (1 of 120), 1.12%

TABLE 5 Detection rates (%) of borer-infested WPM from China, Italy, and Mexico that was inspected as part of the AQIM program during four time periods from 2003 through 2020 that bracket when the US implemented ISPM 15 in 2005–2006.

Country	Period	No. inspections	No. wood borer detections	Detection rate%	% Reduction (*P*-value)
China	2003–2004	159	2	1.26	–
	2005–2006	343	2	0.58	53.7 ($P = 0.378$)
	2007–2009	991	11	1.11	11.8 ($P = 0.555$)
	2010–2020	3,407	25	0.73	41.7 ($P = 0.341$)
Italy	2003–2004	559	4	0.72	–
	2005–2006	1,581	0	0.0	100 ($P = 0.005$)
	2007–2009	2,901	3	0.10	85.6 ($P = 0.016$)
	2010–2020	8,718	20	0.23	67.9 ($P = 0.053$)
Mexico	2003–2004	1,383	4	0.29	–
	2005–2006	3,823	4	0.11	63.7 ($P = 0.136$)
	2007–2009	6,637	5	0.08	74.0 ($P = 0.054$)
	2010–2020	20,551	9	0.04	84.8 ($P = 0.007$)

For each country, detection rates for the three periods from 2005 to 2020 were compared individually to the pre-ISPM 15 period (2003–2004) with a one-sided Fisher's exact test (alpha = 0.1). Analyses were conducted on the final dataset.

during 2007–2009 (4 of 356), and 1.05% during 2010–2020 (10 of 952).

The most common borers detected in WPM from the above five countries varied by country. Cerambycids were the most frequently intercepted wood borers from China (78%), Italy (67%), and Turkey (66%), and usually associated with imports of tiles, stone slabs, metal, and machinery (**Supplementary Table 1**). By contrast, scolytines were the most commonly intercepted borers on goods from Costa Rica (78%) and Mexico (91%) and were mostly associated with imports of perishables goods (**Supplementary Table 1**). Moreover, 88% of the scolytines identified to genus or species from Costa Rica were ambrosia beetles (7 of 8, with 4 others identified to Scolytinae only), whereas 100% were bark beetles in the case of Mexico (6 of 6, with 13 identified to Scolytinae only) (**Supplementary Table 1**).

Discussion

Overview

The current Agriculture Quarantine Inspection Monitoring (AQIM) dataset consists of thousands of records that have been collected at US ports since the late 1990s, from consignments that were randomly selected within various cargo survey categories and uniformly inspected. These qualities give us confidence that AQIM data can be used to compare infestation rates of WPM in several major cargo pathways both before and after US implementation of ISPM 15 during 2005–2006.

We estimated that overall borer detection rates for WPM entering the US in these cargo pathways declined by 36–61% during and after implementation of ISPM 15 (**Table 4**). However, percentage rate reductions by period have lessened over time. In annual terms, detection rates have been relatively constant since 2005, except for a spike in rates associated with Italian tiles from 2015 to 2018 (**Figure 8**). That happened despite the modifications made to ISPM 15, such as the 2009 requirements for debarking, limiting the size of residual bark patches, requiring debarking prior to fumigation, and lengthening the fumigation period.

One feature of our analysis is that AQIM data only started in 2003. Bulman (1992) reported a 4.3% borer detection rate in WPM for randomly selected maritime containerized consignments that entered New Zealand during 1989–1991. Compared to that rate, the three later time periods listed in **Table 4** reflect detection rate reductions of greater than 95%, which would all be highly significant (Fisher's exact test $P < 0.0001$). Many countries were probably already improving the phytosanitary quality of their WPM in the 1990s and early 2000s. For example, beginning in 1992, the European Commission required that pine WPM from countries with pinewood nematode (*Bursaphelenchus xylophilus*) be either fumigated or heat treated before export to Europe (Allen et al., 2017). In 1998, the US required WPM from China to be heat treated, fumigated, or treated with a preservative prior to arrival in the US (US Department of Agriculture Animal and Plant Health Inspection Service [USDA APHIS], 1998). Then, the North American Plant Protection Organization [NAPPO] (2001) drafted and approved a regional standard entitled "Import Requirements for Wood Dunnage and Other Wood Packing Materials into a NAPPO Member Country" (North American Plant Protection Organization [NAPPO], 2001). This regional standard was never implemented because it soon served as the basis for ISPM 15, which was adopted in 2002 (Allen et al., 2017). In addition, several countries implemented ISPM 15 before the US (see Introduction). Thus, it is likely that the pre-ISPM 15 WPM infestation rate would have been significantly greater in the 1990s, if data were available, than the pre-ISPM 15 rate used in the present study for 2003–2004.

It is worth noting that few non-native wood borers have apparently become established in the United States in the last decade. For example, the Eurasian *Quercus*-infesting ambrosia beetle *Xyleborus monographus* was found in California beginning in 2017 (Rabaglia et al., 2020), and the Asian hardwood-infesting cerambycid *Dere thoracica* was found in Georgia starting in 2020 (Traylor et al., 2021). *Xyleborus monographus* has been intercepted seven times during 2009–2021 at US ports, originating from multiple countries and usually in association with WPM. Similarly, *D. thoracica* has been collected multiple times in WPM from China at US ports (Eyre and Haack, 2017; Traylor et al., 2021). Even though these two species were collected only recently, they likely became established many years earlier given the typical lag time between initial establishment and first detection (Brockerhoff and Liebhold, 2017). Another example is the discovery of the *Anoplophora glabripennis* infestation, an Asian cerambycid, in South Carolina in 2020, which was at least seven years old when discovered (Coyle et al., 2021). However, DNA analyses indicated that the South Carolina population matched the current *A. glabripennis* infestation in Ohio that was discovered in 2011, suggesting domestic spread of *A. glabripennis* possibly through movement of infested firewood (Coyle et al., 2021). Alternatively, both *A. glabripennis* infestations could have been two separate introductions that originated from the same source population in Asia. Given that annual volume of imports to the US has increased 68% from 2003 to 2020, while borer detection rates have remained rather steady, an increase in introductions and establishments might be expected. However, the apparent lower establishment rates for wood borers in recent years, compared to the late 1990s and early 2000s (Haack, 2006), suggests that ISPM 15 is helping to mitigate risks in the US and remains an important component of the global phytosanitary system.

Possible factors influencing the impact of International Standards for Phytosanitary Measures 15

Although we anticipated that borer detection rates in WPM would consistently decline with implementation of each ISPM 15 rule change, there are several possible explanations for why infestation rates have remained fairly stable since 2005. The six explanations reviewed in detail by Haack et al. (2014) remain relevant to the current study. Briefly, they were (1) wood borer tolerance to the approved treatments, especially heat treatment at 56°C for 30 min, (2) unintentional non-compliance due to factors like poorly calibrated equipment, (3) outright fraud where WPM is stamped with an ISPM 15 mark without treatment, (4) colonization of WPM by borers after proper treatment, (5) data issues with AQIM such as pest detections being recorded on a consignment basis, and (6) artificially low pre-ISPM 15 detection rates because some shippers started using treated WPM when exporting to the US in anticipation of its implementation in 2005. To this list, we add the possibilities that (7) borer detection has increased over time by inspectors, (8) changes in trading partners that may vary in ISPM 15 enforcement and implementation, as well as the diversity of local borers, (9) variability in the occurrence of borer outbreaks among trading partners, and (10) limits on the compliance levels that can be achieved under an international standard such as this one.

With respect to thermotolerance by wood borers, it is important to recognize that the primary heat treatment schedule adopted in ISPM 15 (56°C for 30 min throughout the profile of the wood including the core) was initially developed to kill pinewood nematode (Allen et al., 2017), with the recognition that some wood pests were able to tolerate those conditions (Haack et al., 2014). For example, the Asian buprestid beetle known as emerald ash borer, *Agrilus planipennis*, was the focus of many heat-treatment studies after its initial discovery in the US in 2002 (see discussion in Haack et al., 2014). Some authors reported various levels of *A. planipennis* survival after heat treatment, but none precisely tested 56°C for 30 min at the core of the wood, which is the ISPM 15 requirement (Allen et al., 2017; Food and Agriculture Organization [FAO], 2019). Based on studies by Myers et al. (2009), the heat treatment schedule for interstate movement of ash (*Fraxinus*) firewood within the US was set at 60°C for 60 min, but the data supporting this new schedule was not considered sufficient to change import regulations by the European Commission (European Food Safety Authority Panel on Plant Health [EFSA PLA], 2012).

More recently, MacQuarrie et al. (2020) and Haack and Petrice (2022) reported complete mortality of *A. planipennis* when heat-treating infested wood to the current standard. However, Haack and Petrice (2022) demonstrated that some borers did survive in both hardwood and conifer bolts when treated at 56°C for 30 min. Moreover, they showed that borer mortality increased as the air temperature in the heating chamber was increased from 60° to 75°C (testing at 60°, 65°, 70°, and 75°C). Given these recently published findings, and that ISPM 15 does not stipulate a minimum chamber temperature during heating cycles, a proportion of the live borers found in heat-treated WPM by the AQIM program from 2005 to 2020 likely did survive heat treatment. Studies are currently underway to test *in vitro* lethal temperatures of various borers using a precision water bath apparatus that should help reduce the confounding effects of the thermal properties of wood on heat treatment testing of borers (Noseworthy et al., 2022).

Unintentional non-compliance can occur when managers attempt but fail to apply the appropriate heat treatment or fumigant dose to all WPM during a treatment cycle

(Haack et al., 2014). Factors such as poor equipment calibration, cold pockets, and improper sensor placement or stacking of WPM in kilns, among others, can all lead to uneven treatment, with some WPM pieces not reaching the minimum dose. Therefore, the occurrence of some live borers could reflect such situations. Many recommendations on how WPM is to be handled and tested during heat treatment and fumigation sessions have been published by the IPPC (Food and Agriculture Organization [FAO], 2017). Additionally, fraud can occur when non-treated WPM is stamped with the ISPM 15 mark and used to export cargo (Pallet Enterprise, 2015; Eyre et al., 2018; Papyrakis and Tasciotti, 2019). The incidence of this type of fraud at a global scale is unknown, given that each trading partner's National Plant Protection Organization is responsible for their own respective audits and ISPM 15 compliance. Unfortunately, no effective diagnostic tools exist that can independently test WPM for treatment compliance, although methods have been investigated (Iline et al., 2014; Kim et al., 2019). While over 98% of the WPM entering the US in the past decade has been stamped as ISPM 15 compliant (**Figure 2**), it is also true that all live insects evaluated in this paper were within stamped and apparently compliant WPM.

Post-treatment colonization of WPM can occur, especially when large patches of bark are retained on WPM (Evans, 2007; Haack and Petrice, 2009). A few borers can infest bark-free wood, including some ambrosia beetles and cerambycids, but most require bark to be present during colonization, oviposition, and early larval development (Duffy, 1953; Haack and Petrice, 2009; Haack et al., 2017). This fact was the rationale for requiring WPM to be made from debarked wood in 2009, which significantly (Fisher's exact test $P < 0.0001$) decreased the percentage of marked WPM entering the US with bark from 2.3% in 2007–2009 (481 of 20,635 records) to 1.2% in 2010–2020 (905 of 71,887). The requirement for debarking WPM is likely the reason why fewer true bark beetles (that develop under bark) have been detected in WPM in recent years compared with ambrosia beetles (that develop in wood) (see discussion above and **Supplementary Table 1**). Nevertheless, it is possible that a few of the wood borers found in WPM in the present study, such as some ambrosia beetles, colonized the WPM after treatment.

With respect to AQIM data collection protocols, detections of wood borers are reported for an entire consignment, giving taxonomic information for the wood pests found but not the total number of individuals found, nor the number of infested pieces of WPM. Consequently, borer infestation evaluated at the per-WPM-piece level could have fallen dramatically over time, but analyses at the consignment level cannot uncover such trends. For example, Schortemeyer et al. (2011) presented worst-case infestation levels of *Agrilus planipennis* for a typical pallet where every piece of wood used to construct the pallet was considered infested at typical field levels. They calculated that such a pallet could contain as many as 38 *A. planipennis* larvae. If double stacked, a 40-foot-long shipping container with 44 pallets infested at worst-case levels could yield 1,672 *A. planipennis*. Alternatively, if a consignment had just one *A. planipennis* infested pallet at the worst-case level, and further if that pallet's ISPM 15 treatment had killed 95% of the borers present, then there would be only about two *A. planipennis* individuals present per container. In each situation, the two containers would be recorded as infested in AQIM, but the worst-case founder population of 1,672 *A. planipennis* individuals clearly poses a much greater risk of establishment than the ISPM 15-mitigated risk founder population of 2 individuals, especially when considering Allee effects (Liebhold and Tobin, 2008; Brockerhoff et al., 2014; Ormsby, 2022). Moreover, pest establishment is less likely if the entering imported cargo goes to disparate geographic locations, because surviving insects need to find both suitable host plants and potential mates (if sexually reproducing).

All the above analyses assumed that the detection abilities of port inspectors were uniform over time. However, Agricultural Specialists for the US Customs and Border Protection might be detecting wood borers more reliably than before because of improvements in training, inspection techniques, or technology. If so, the apparent impact of ISPM 15 would be lessened in recent years. Estimating the effectiveness of inspections is not currently possible, which typically requires a "leakage survey" conducted on inspected goods to see how often target pests are missed (Robinson et al., 2009).

Changes in trading partners could also influence the apparent effectiveness of ISPM 15, especially if countries vary widely in the quality of enforcement and implementation of ISPM 15 (Papyrakis and Tasciotti, 2019). For example, based on recent borer detection trends (**Table 5**) the phytosanitary quality of WPM appears to have improved over time in Mexico, stayed rather steady in China, and declined in Costa Rica and Turkey (see discussion above). Infestation rates on WPM from Italy have generally improved over time as well (**Table 5**), except for a recent rate spike (see above). In addition, given that species of trees and their associated borers often vary by country and world region, changes in trading partners can affect both the type of wood used to construct WPM and the composition of associated borers.

Even when trading partners do not change, local outbreaks of both native and non-native wood borers can influence which tree species are used to construct WPM at the origin, and their potential pest load. For example, borer outbreaks often follow periods of environmental stress such as drought, severe and repeated defoliation, and widespread wind damage (Haack and Petrice, 2019; Pureswaran et al., 2022). Wood from such trees could be heavily infested, with high pest loads prior to any ISPM 15 treatment. If the treatments are not 100% effective, then live borers would likely be more commonly encountered in WPM during outbreak periods. In addition, planting non-native tree species can lead to outbreaks of native borers. For example, in China, outbreaks of the native buprestid *Agrilus planipennis* occurred in areas planted to North American ash (*Fraxinus*) (Dang et al., 2022). Similarly, outbreaks in China of the native cerambycid *A. glabripennis* occurred in areas planted to non-native poplars (*Populus*) (Haack et al., 2010). In both cases, widespread ash and poplar mortality occurred, especially in the 1990s. Some of these dead and dying trees were likely used to construct WPM, which then could have resulted in these two Asian borers being introduced to the US and other countries (Haack et al., 2010; Dang et al., 2022).

Still, the influence of changes to ISPM 15 treatment requirements alone may not always lead to reduced wood borer infestation rates. This is because in an open international commercial system such as this, program integrity depends on voluntary compliance (Fletcher et al., 2017; Yoe et al., 2020; Meyerson et al., 2022). Reducing infestation levels to near zero principally via application of the ISPM 15 standard would require nearly universal compliance by industry, using highly effective treatments. However, that may be difficult to achieve without either very strong incentives (Rossiter and Hester, 2017) or intensive oversight and significant penalties for non-compliant exporters (Hood et al., 2019). Improved ISPM 15 education and outreach by IPPC, along with greater cooperation and information sharing amongst importing and exporting countries, could create global feedback that facilitates a very high proportion of WPM in the system becoming compliant.

Wood borer diversity

The diversity of borers reported in WPM in the present study increased from two major borer groups in 2003–2004 to seven in 2010–2020 (**Table 1**). In part, this outcome reflects the longer 2010–2020 sampling period, along with many more countries being sampled in 2010–2020 (159 vs 75) and more countries being the source of infested WPM in 2010–2020 than in 2003–2004 (25 vs. 5). Moreover, as the number of trading partners increases for any country it is also likely that the number of tree species used to construct WPM will increase (Krishnankutty et al., 2020), along with borer diversity, thus increasing the species pool of potential invasive wood borers. Nevertheless, although borer diversity increased over time in the present study (**Table 3**), all the major families of borers intercepted during the 2010–2020 period have been collected in WPM at US ports in earlier decades (Haack, 2001, 2006) as well as in other countries (Bain, 1977).

Conclusion

Environmental standards such as ISPM 15 have both costs and benefits (Papyrakis and Tasciotti, 2021; Meyerson et al., 2022). The main objective of ISPM 15 is to lower the risk of moving wood pests through solid wood packaging used in international trade and thereby reduce the risk of establishment and resultant negative impacts on woody plants in importing countries. In addition, standards like ISPM 15 allow compliant products to demonstrate reduced risk, and thereby remain viable for use in international markets once most countries have adopted the standard. Moreover, once most importing and exporting countries have adopted ISPM 15, the inspection process at ports should be expedited because in theory the ISPM 15 mark should indicate full treatment compliance, reducing the need for high frequency inspections and decreasing the need for supplemental paperwork such as phytosanitary certificates. As for the economic costs of compliance with ISPM 15, there are both direct costs for the equipment to heat treat or fumigate WPM, and indirect costs such as training employees at treatment facilities and administrative record keeping by treatment facilities and National Plant Protection Organizations. There are also monitoring and enforcement costs for both exporting and importing countries, plus the environmental costs of fumigants and the carbon emissions related to the energy used to heat wood.

Our analysis of the AQIM data indicated that borer detection rates decreased markedly following the implementation of ISPM 15. However, the magnitudes of these trends varied among survey programs, exporting countries, and time spans. Nevertheless, recent borer detection rates are dramatically lower than those reported by Bulman (1992) for 1989–1991. However, given that international trade volume continues to increase each year with tens of millions of consignments having associated WPM, the relatively low risk of WPM infestation when evaluated at the actual scale of trade indicates that WPM still poses a real risk for pest introduction. The risk of establishment, however, may be much lower if the founder population is small. The collection of WPM data in AQIM could be improved by recording, for example, the numbers of infested units within consignments, specifying when bark is present if the residual pieces are larger than the current tolerance limits, and the type of treatment specified on any infested piece of WPM according to the ISPM 15 mark. Such information would allow for a clearer assessment of the actual risk of individual infested consignments.

Opportunities exist to improve ISPM 15 implementation and enforcement in many countries (Papyrakis and Tasciotti, 2019). For example, some countries need improved training on how to (a) properly treat, mark, and repair WPM, (b) meet the record-keeping requirements of ISPM 15, and (c) inspect facilities performing heat treatments and fumigations. In other cases, enhanced cooperation between trading partners could reduce fraud incidence, leading to reductions of apparently compliant WPM bearing live pests. Modifications to ISPM 15 could be considered when technical advancements are made in fumigants, sensors, and treatment schedules and techniques. Nonetheless, the near global acceptance of ISPM 15 over the past two decades indicates a strong commitment by the world community to minimize movement of wood pests in WPM through international trade.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: Besides the **Supplementary material** provided with this manuscript the remaining raw data supporting the conclusions of this article are considered sensitive and are subject to data agreements with the U.S. Department of Agriculture, Animal and Plant Health Inspection Service (APHIS). Requests to access these datasets should be directed to BC, barney.p.caton@usda.gov; JH, jesse.a.hardin@usda.gov.

Author contributions

RH, JH, BC, and TP conceived and designed the analyses. JH and BC obtained and organized the initial dataset. RH and TP evaluated all insect interceptions. RH prepared the initial manuscript. All authors contributed to the data analysis and interpretation of the results, and contributed to the editing various drafts of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2022.1069117/full#supplementary-material

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