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REVIEW

Exploring pest mitigation research and management associated with the global wood packaging supply chain: What and where are the weak links?

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Abstract Global trade continues to increase in volume, speed, geographic scope, diversity of goods, and types of conveyances, which has resulted in a parallel increase in both quantity and types of pathways available for plant pests to move via trade. Wood packaging material (WPM) such as dunnage, pallets, crates, and spools, is an integral part of the global supply chain due to its function in containing, protecting, and supporting the movement of traded commodities. The use of untreated solid wood for WPM introduces the risk of wood boring and wood-infesting organisms into the supply chain, while the handling and storage conditions of treated WPM presents risk of post-treatment contamination by surface-adhering or sheltering pests. The wood-boring and -infesting pest risks intrinsic to the solid wood packaging pathway were addressed in the 2002 adoption and 2009 revision of ISPM 15, which was first implemented in 2005–2006 in North America. Although this global initiative has been widely implemented, some pest movement still occurs due to a combination of factors including; fraud, use of untreated material, insufficient- or incomplete- treatment, and post-treatment contamination. Here we examine the forest-to-recycling production and utilization chain for wood packaging material with respect to the dynamics of wood-infesting and contaminating pest incidence within the environments of the international supply chain and provide opportunities for improvements in pest risk reduction. We detail and discuss each step of the chain, the current systems in place, and regulatory environments. We discuss knowledge gaps, research opportunities and recommendations for improvements for each step. This big picture perspective allows for a full system review of where new or improved pest risk management strategies could be explored to improve our current knowledge and regulations.

Keywords Contaminating · Dunnage · Infesting · Invasion pathways · Invasive species · Non-indigenous pests · Pallets · Wood packaging material

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Introduction

The first International Year of Plant Health (IYPH) in 2020 and early 2021 was proposed to renew and reinvigorate a global focus on tactics to protect the environment, conserve biodiversity, slow climate change, and protect the world's food production and natural resources (IPPC 2021a). The IYPH was necessary because invasive pests in all ecosystems are estimated to cost the world tens of billions of dollars annually (Bradshaw et al. 2016; Diagne et al. 2021) and have an annual cost of over $22.1 billion in North America alone (Crystal-Ornelas et al. 2021; Rico-Sánchez et al. 2021) although it is widely accepted the true costs are likely greater. Many invasive species are pests of trees and forests, where their damage can also affect forest productivity, ecosystem services, and carbon sequestration (Jones 2016; Fei et al. 2019; Quirion et al. 2021). Since potential plant pests can be inadvertently moved via international trade (Allen and Humble 2002), finding ways to reduce the risk of plant pest movement in traded commodities and their conveyances is one important step toward these goals.

The expansion of global trade over the past several decades has opened new markets and increased the speed at which goods move around the world. This rapid increase in trade volume is partly due to a growing global population with increased purchasing power and a corresponding increased demand for goods. One consequence of these phenomena is a global increase in plant, animal, and microorganism movements associated with trade commodities that can lead to the introduction and establishment of invasive pests (Banks et al. 2015). The global phytosanitary community works collectively to develop solutions to address the risks associated with trade such as those posed by invasive pests and the movement of untreated solid wood packaging material (WPM, Fig. 1).

While earlier (mid-1800s to early-mid 1900s) introductions of invasive species to North America often occurred via trade in infested plants, most recent introductions (e.g., *Anoplophora glabripennis*, *Agrilus planipennis*) are thought to have been introduced via WPM. International standards for phytosanitary measures (ISPMs—developed under the auspices of the International Plant Protection Convention) and regional standards for phytosanitary measures (RSPMs—developed under the auspices of regional plant protection organizations like the North American Plant Protection Organization) are guidelines used for phytosanitary trade. These guidelines can be used by countries or the global community to develop regulations to reduce the risk of non-indigenous species introductions associated with specific commodities or conveyances. The standard addressing the risk of wood boring and wood infesting pests in WPM is *ISPM 15: Regulation of wood packaging material in international trade* which sets the requirements for acceptable treatments of WPM (IPPC 2019). Other ISPMs provide guidelines for reducing the risk of infesting organisms in plants (ISPM 36; IPPC 2016), on vehicles, machinery, and equipment (ISPM 41; IPPC 2017b), and integrating measures in a systems approach for pest risk management (ISPM 14; IPPC 2021c and RSPM 41; NAPPO 2018).

International awareness of the risk posed by contaminating organisms has resulted in a renewed interest to determine how and why these potential invasive pests are moved within global supply chains (e.g., NAPPO 2022). Integral to the understanding of contaminating (also referred to as "hitchhiking") organisms and their control is differentiating among the functional niches of non-indigenous species. Infesting organisms infect or invade plant tissues whereas contaminating organisms lack this physical or physiological relationship with the article on which they are found. Because contaminating organisms can be found on any packaging material or conveyance, their presence in the WPM supply chain is not unique. However, this risk can only be addressed when we understand how the regulatory and logistical conditions affecting supply chains already influence the risk posed by contaminating organisms. With this information, the phytosanitary community can then develop new and more effective strategies to minimize the risks present in the global supply chain.

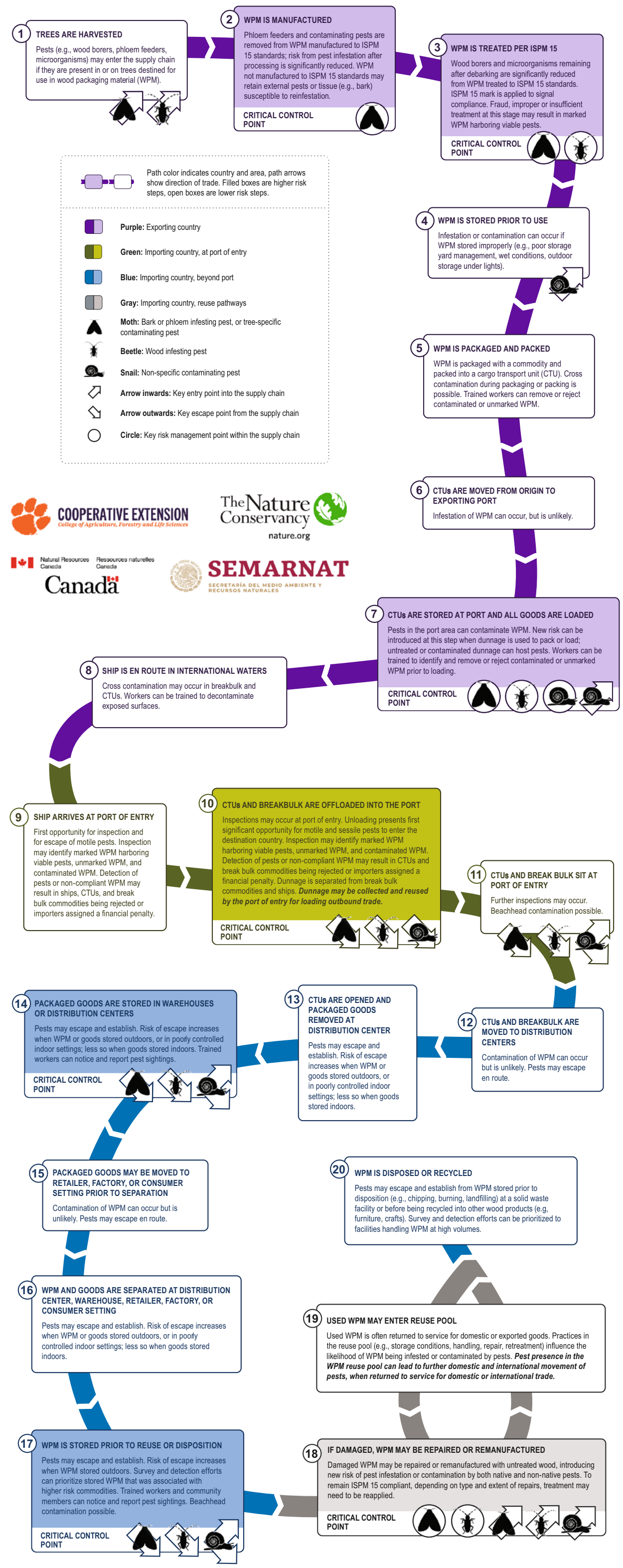
To understand how WPM may affect the risk of introducing organisms we created a schematic representation of a "typical" global supply chain. Our example supply chain follows a commodity created overseas that will be delivered to a consumer somewhere in North America (Fig. 2). We then use the example to review how the activities at different steps influence where, when, and how unwanted organisms can potentially enter and exit a supply chain. We focus on WPM and present a supply chain that terminates in North America as an example; however, this

Fig. 1 Wood packaging material (WPM) is the term for solid wood products used to aid in the transportation, protection, or containment of commodities. Wooden pallets (**A**) are the most common WPM used to facilitate the movement of packaged and bulk goods within warehouses, in trucking, and in shipping containers. Wooden packaging like spools (**B**), crates (**C**), cases or frames that contain or protect a commodity are also WPM. Blocks, strapping, and other wooden materials used to secure loose goods from damage or unwanted movement while in transport are also WPM and collectively are referred to as dunnage (**D**). Dunnage can be used within conveyances like sea containers to prevent the movement of goods, or within the holds of ships either as a counterbalance for ship stability or to restrain break-bulk cargo (commodities too large or otherwise unsuitable for shipping containers). Photo credits: LF Greenwood (**A**, **C**), DR Coyle (**B**) Susan C Usman (**D**)

is globally relevant as many goods are moved with WPM and many of the phytosanitary risk reduction principles we review are relevant for other commodities, conveyances, and supply chains.

The literature on preventing and managing the spread of organisms from one place to another uses a range of terms to describe these species (Iannone et al. 2021). Numerous attempts have been made to standardize the terminology within theoretical frameworks and models (e.g., Richardson et al. 2000; Kolar and Lodge 2001; Colautti and MacIsaac 2004; Catford et al. 2009) but not without some controversy (e.g., Sagoff 2005; Boltovskoy et al. 2018). Most of these frameworks focus on the steps of invasion as a species transitions from its first introduction to a new place, through its establishment, spread, and integration with the local ecosystem and the attendant impacts. Within those frameworks, we focus on the transport and entry of species (e.g., Catford et al. 2009) and how phytosanitary measures can prevent their establishment, spread, and impact. Consistent with its use in invasion ecology, we use the term non-indigenous species to refer to species introduced beyond their native range due to human activity (Kolar and Lodge 2001) and indigenous species to refer to species within their native range. This

Fig. 2 Flow chart identifying where infesting and contaminating pests may enter and escape wood packaging material in the supply chain. The chart shows movement of WPM from source to destination; WPM as it is produced in its source country, enters the supply chain, becomes associated with goods, is transported to North America, is disassociated from its goods, and then either disposed of or reused



use is also consistent with International Plant Protection Convention (IPPC) and ISPM usage (e.g., IPPC 2021b). We use the term 'pest' to refer to a species that has harmful impacts (e.g., to the environment or to an economy) in its native or introduced range.

This review is presented in sections that correspond to our example global supply chain which follows a piece of WPM as it is produced, enters the supply chain, becomes associated with goods, is transported to North America, is disassociated from its goods, and then either disposed of or reused (Fig. 2). We review some of the challenges associated with mitigating the risk of invasive pests along supply chains and provide suggestions for areas of research that could address these challenges.

Trees are harvested (Fig. 2, Box 1)

The first step in the creation of WPM occurs when a tree is harvested. Insects, fungi, nematodes, and many other organisms use trees as a resource, most commonly for food, shelter, or as a substrate for oviposition. These organisms can potentially be present in WPM and be transported anywhere in the world if they are not removed or rendered infertile, inactive, unable to complete development or reproduce, or killed.

The types of organisms that use trees and the tree tissues they use varies among species and groups. For example, live trees may contain bark beetles (Scolytinae), which consume live phloem tissue and are found on the phloem-inner bark interface (Lieutier et al. 2004; Vega and Hofstetter 2015). Cerambycidae and Buprestidae larvae usually consume phloem but can also be found feeding and living in the sapwood and heartwood (Lieutier et al. 2004; Haack et al. 2017). Siricidae larvae and some Scolytinae (e.g., ambrosia beetles) live in the sapwood and heartwood (Schiff et al. 2012; Hulcr and Stelinski 2017). Other insects (e.g., *Lymantria dispar*, *Lycorma delicatula*) attach eggs or pupae to surfaces, including standing or downed trees (Elkinton and Liebhold 1990; Liu 2019) and some insects (e.g., *Halyamorpha halys, Orcheses fagi*) may overwinter within the bark of trees (Lee et al. 2014; Morrison et al. 2017). Fungi and other microorganisms may be introduced to trees via insect or mechanical damage, and windblown spores may infect foliage or wounds on a tree.

Pest population densities increase and decrease over time and the periodic or episodic outbreaks experienced by some pests may be caused by natural or anthropogenic factors, such as climate change or monocultures. These outbreaks can result in the increased probability that pests may be in wood destined to become WPM. For example, the planting of *Populus* monocultures for windbreaks in China led to elevated *A. glabripennis* populations in the 1960s–1990s (Haack et al. 2010; Yan and Qin 1992) which may have contributed to their introduction to the United States sometime prior to their first discovery in 1996 (Haack et al. 1996). Non-indigenous pest species may also have elevated populations in their invaded range, like *H. halys* in the U.S. (Valentin et al. 2017) and *Pityophthorus juglandis* in Italy (EPPO 2015). These are sometimes referred to as beachhead or bridgehead populations (Lombaert et al. 2010; Bertelsmeier and Keller 2018), which may result in increased infestation or contamination of WPM in the new range and subsequent export to other countries.

The timing of the harvest process also affects the number of pests and other organisms that can enter the WPM production chain. If trees are harvested when pests are not present or are present in low numbers, the risk of pest introduction is lower. Likewise, if trees are harvested in an area with a high pest density (e.g., salvage logging due to a bark beetle outbreak) the risk of that pest's presence in the WPM chain is greater. Insects can also be attracted to fallen trees associated with blow-down events (e.g., hurricanes, windstorms; Vogt et al. 2020) resulting in significant population increases. However, harvesting activities can also mitigate this threat, as debarking round wood (i.e., logs) at the harvest site removes most of the pests that live on or in the bark and phloem layer (e.g., Thorn et al. 2016) and some pests may be dislodged from round wood as it is transported to a processing facility. Organisms living inside the sapwood and heartwood have a higher likelihood of surviving harvest, and harvesting processes that minimize bark disturbances will increase the survivorship of organisms that have colonized the outer surfaces of round wood.

Round wood is often piled and stored at the harvest site or at processing facilities (Fig. 3A), and organisms that are attracted to recently cut trees may enter the wood and thus the WPM chain. Several insect and

Fig. 3 In the sawn wood production process, round wood (**A**) is first mechanically debarked, using machinery such as a rotary-head debarker (**B**). Debarked wood (**C**) may show evidence of insect damage (arrow 1) and can still retain some patches of bark (arrow 2). Debarked wood is then milled to produce sawn wood (**D**) of different dimensions and grades, some of which may be used for solid wood packaging material. Photo credits: CJK MacQuarrie

fungal species attack milled untreated wood and lumber and can persist inside this material for some time (Verrall 1945; Gray and Borden 1985; McLean 1985; Peters et al. 2002; but see Haack and Petrice 2009). Various management tactics (e.g., rapid removal of harvested round wood immediately after harvest, harvesting during seasons when pests are not active, application of pesticides, anti-aggregation pheromones, or water) may prevent or reduce pest infestation of stored round wood.

WPM is manufactured (Fig. 2, Box 2)

Wood packaging material is defined by the IPPC, as "wood or wood products…used in supporting, protecting or carrying a commodity" (IPPC 2021b). This definition excludes paper products (like cardboard boxes) but includes dunnage (IPPC 2021b). Within ISPM 15 crates, boxes, packing cases, dunnage, pallets, cable drums, spools and reels are all considered WPM, but the standard exempts WPM made from thin wood (less than or equal to 6 mm thickness) and processed wood material (e.g., plywood, particle board, etc.). While WPM is often referred to as solid wood packaging material to differentiate it from WPM made of processed wood; we refer here to WPM in keeping with the IPPC definition and ISPM 15 understanding. WPM is typically constructed from sawn wood, i.e., rectangular pieces of different dimensions that have been sawn from round wood, or what is more commonly referred to in North America as 'lumber'.

Debarking is a part of most sawn wood production processes. In debarking, round wood (Fig. 3A) is subjected to a physical process to remove the bark (e.g., using a rotating instrument or scraping with hand tools; Fig. 3B). Most organisms that live in and just under the bark will be removed from the round wood during this process (Jones et al. 2013; MacQuarrie et al. 2020). In practice, debarking often does not remove all the bark from a piece of round wood (Fig. 3C). Trees do not grow perfectly round and excessive debarking would be required to address the natural variations in the shape of the tree stem, which could damage the underlying wood and reduce the yield. Debarking is only intended to remove most of the bark; any remaining bark is removed from sawn wood during subsequent steps of the milling process (see MacQuarrie et al. 2020 for discussion). Thus, wood that has been through this process is referred to as "debarked" and not "bark free." After debarking, the round wood is processed into sawn wood of various dimensions (Fig. 3D).

In a sawmill, wood may be processed for multiple uses, with better quality sawn wood (i.e., wood without visual and structural defects) allocated to the production of high-value goods or construction materials. Lower quality wood (with more visual and structural defects) can include the outer sawn wood or slabs (i.e., wood that may still have some rounded profile) or edges (i.e., the waste created when sawn wood is cut longitudinally to achieve the desired dimension) that are a by-product of creating higher grades of sawn wood. This lower quality wood is often used for other purposes, including WPM. WPM can be constructed from lower quality wood, or wood that is not suitable for other uses due to structural defects. This lower quality wood may be sourced from poor quality or low value tree species, trees impacted by disturbances such as windthrow or fire, or trees that have been killed by pests. Sawn wood can then be used to manufacture items such as pallets, reels, or crates (Fig. 1A-C). Dunnage (Fig. 1D) is another class of WPM; it is most often single pieces of whole wood in standardized or custom cut shapes and sizes. Dunnage is used primarily for stabilizing cargo during transit. There are also processed wood or paper products (e.g., oriented strand board, particle board, molded wood fiber, cardboard) used in the construction of WPM (Fig. 4). Creating processed wood products (e.g., chipping) kills most of the insects present in the wood (McCullough et al. 2007; Allen et al. 2017). Additional processing steps such as compression, heating, and gluing further reduce the phytosanitary risks of processed wood products.

WPM is treated per ISPM 15 (Fig. 2, Box 3)

Sawn wood intended for use in WPM destined for international trade must be compliant with ISPM 15 (IPPC 2019). The process to produce compliant sawn wood has three primary components: (1) a specific criterion for debarking, (2) an approved application of heat or other treatment (e.g., fumigation) of the wood, and (3) a mark to indicate the WPM has been subjected to an approved phytosanitary treatment. Prior to 2009, the goal of compliance with ISPM 15 was to render the risk of woodborne pests "practically eliminated," in 2009 the standard was amended to "significantly reduced" (IPPC 2019). The ISPM 15 standard does not specify an acceptable survival or mortality rate for any taxonomic group exposed to treatment, nor does it state a number of viable pests that are allowed to be present by any defined measure (i.e. not by; per individual piece of wood, per unit of packaging, or per consignment.) The quantification and administration of measures and treatments is instead the responsibility of National Plant Protection Organizations (NPPO) of each of the IPPC's contracting parties.

Debarking is intended to prevent pest infestation of bark or underlying phloem (Haack and Petrice 2009) following heat or fumigation treatment. However, wood used to construct WPM can still retain some bark and the WPM will still be compliant with ISPM 15, but that bark must be less than 3 cm wide or, if the piece is longer than 3 cm, smaller than 50 cm^2 in area (IPPC 2019). Wood boring insects or microorganisms may still be living in these small bark pieces or deeper in the wood; if present, these organisms should be addressed by the subsequent heat or fumigation treatments. Allowing a small amount of bark to be retained means that there is a risk that post-treatment pests might re-infest the WPM. However, these allowances in ISPM 15 are based on the low probability of bark and wood boring insects completing

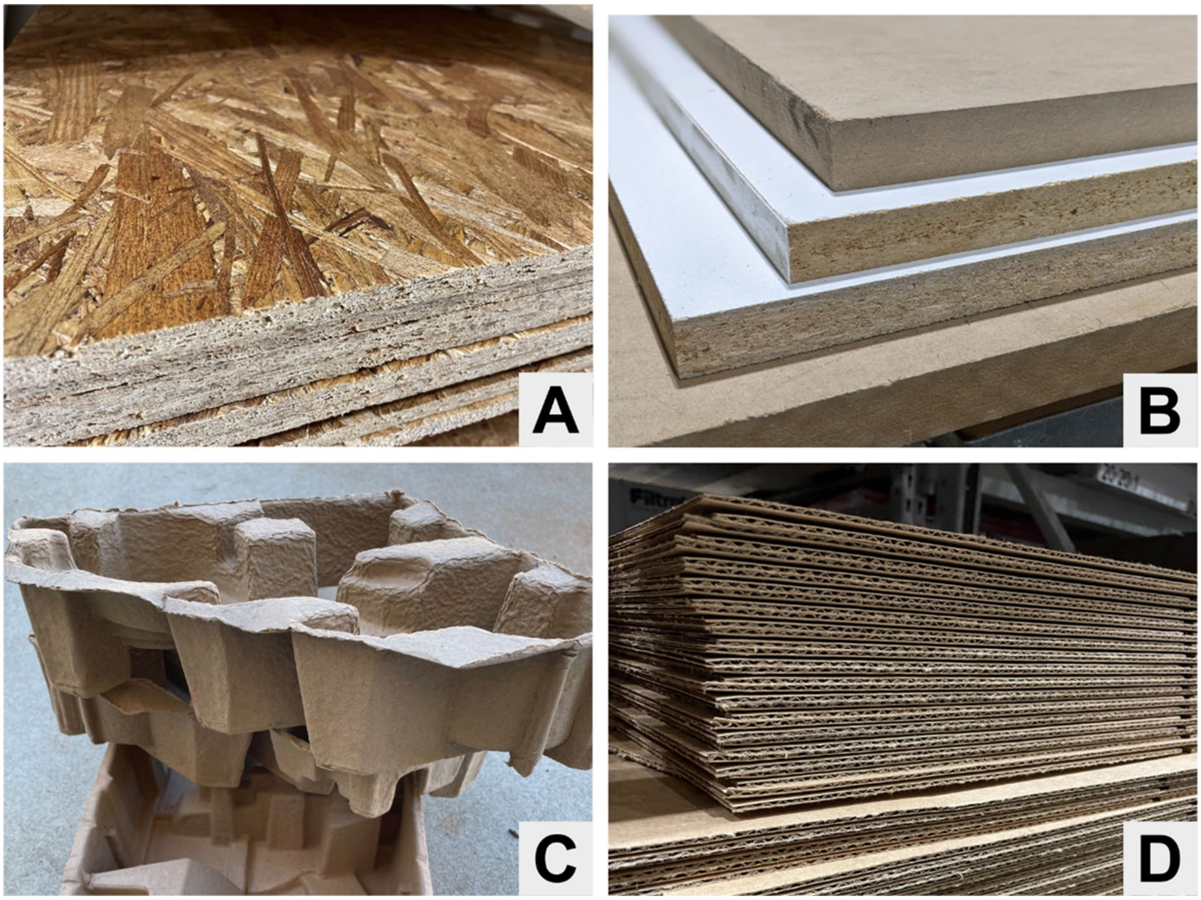


Fig. 4 Manufactured wood and paper products used in the transport, protection, and containment of commodities not considered to be solid wood packaging material (**A**: oriented strand board, **B**: particle board, **C**: compressed fiber, **D**: cardboard). The manufacturing process used to create these products reduces wood to a dimension that is functionally non-survivable for organisms present at the time of manufacturing. Photo credits: DR Coyle (**A, C, D**), CJK MacQuarrie (**B**)

development if they infest the WPM after it has been treated (Haack and Petrice 2009).

The approved treatments are intended to kill organisms that remain in or on wood after the debarking and milling process (e.g., Mayfield et al. 2014; Mackes et al. 2016). Wood destined for use as WPM must undergo one of three currently approved treatments: heat treatment at 56 °C for 30 min where the temperature is measured throughout the entire profile of the wood, dielectric heating (microwaving) to 60 °C for 1 min where the temperature is measured at the surface of the material, or fumigation by sulfuryl fluoride or methyl bromide to a minimum concentration–time product and residual concentration over 24 h (IPPC 2019). The heating methods are intended to damage cell contents and structures of pests, thereby rendering them inactive, unable to complete development or reproduce, or dead (NAPPO 2014). The use of methyl bromide is being reduced or phased out by many countries because of its negative impact on the ozone layer (Besri 2010; IPPC 2008) as well as due to human health concerns. It is explicitly stated in the standard's documentation that none of these approved treatments are designed to provide post-treatment protection from contaminating pests (IPPC 2019).

The final component of ISPM 15 is the application of an official mark to the WPM (Fig. 5A, B). WPM lacking this mark, or with the mark incompletely or incorrectly applied, is considered non-compliant. The mark (also called a stamp) allows for visual confirmation that the WPM has been treated and gives the specific treatment (e.g., HT for heat treatment), the country of origin and the treatment facility. The mark is applied under the authority of the national plant protection organization (NPPO) of the country where the WPM is manufactured and the mark must conform to ISPM 15 specifications (IPPC 2019; Sela et al. 2017). To ensure that WPM is properly treated, NPPOs certify and audit ISPM 15 treatment facilities. When non-compliant WPM is found outside of its country of origin, the NPPO of the importing country is responsible for notifying the NPPO of the exporting country (if WPM is not marked) or country of WPM origin and certification (if the ISPM 15 mark is present; this is often, but not always, the exporting country). The exporting or certifying NPPO is then responsible for tracing the source of the non-compliant material and taking necessary and/or appropriate actions with the certifying facility. Zahid et al. (2008) found that non-compliance due to improper marks varied widely, based on year, origin of the WPM, and commodity. As countries implemented the standard in the years following ISPM 15 adoption, presence and quality of marks improved.

At this point in the supply chain, following fully compliant treatment, WPM has significantly reduced risk of spreading wood infesting pests. The following sections therefore address the risks associated with use in the supply chain of untreated WPM, inadequately or insufficiently treated WPM, fraudulently stamped untreated WPM, or WPM that has been exposed to contaminating organisms.

WPM is stored, then packaged and packed (Fig. 2, Boxes 4 and 5)

Newly treated WPM produced at a WPM manufacturer is often stored for a period before being loaded with goods. During this storage period treated WPM may become infested or contaminated with wood specific post-treatment pests, such as bostrichids (Haack and Petrice 2009) and surface or crevice contaminating pests (e.g., *L. dispar*, *L. delicatula*, *H. halys*). This can happen at the manufacturing facility, or at the location where the WPM is associated with commodities (e.g., boxes placed on a pallet, wire reeled on a spool—this process is referred to as 'packaging'). During the packaging process, WPM is at risk of becoming contaminated with pests if it comes into

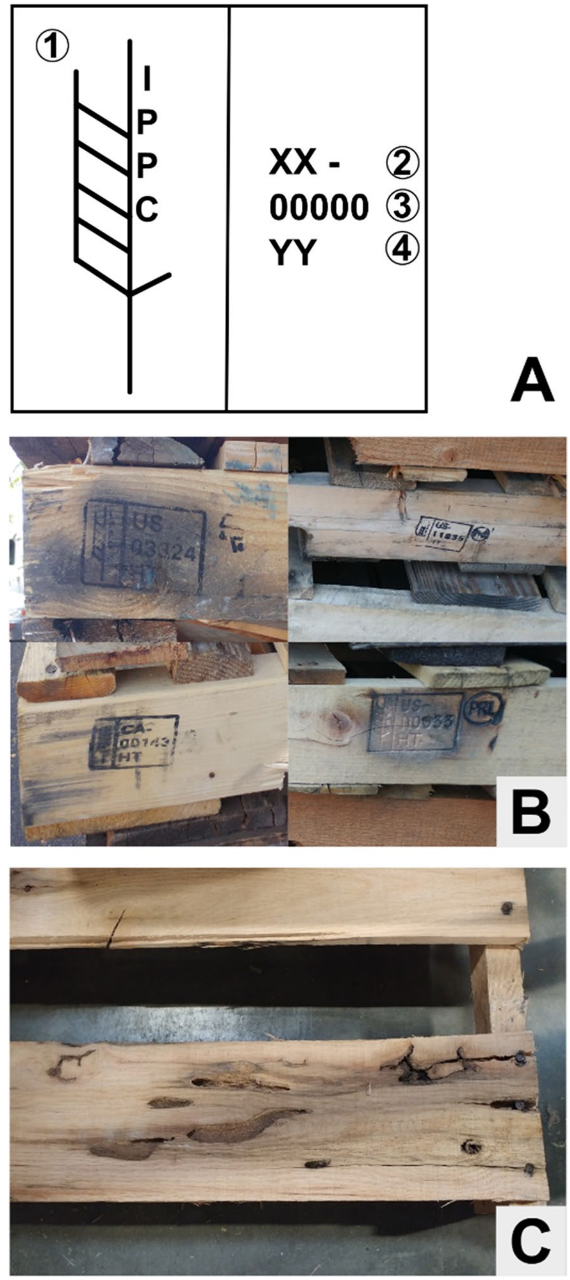


Fig. 5 An example (**A**) of the mark required under the International Standard for Phytosanitary Measures (ISPM 15): Regulation of Wood Packaging Material in International Trade. Each mark is required to show the International Plant Protection Code (IPPC) logo (1); the country code (2); the facility code where treatment was applied (3) and the type of treatment applied (4); versions of that mark (**B**) as applied to pallets; and a pallet showing pre-milling insect damage (**C**). Illustration by CJK MacQuarrie; Photo credits: LF Greenwood

contact with other infested or contaminated objects or environments (e.g., commodity, piece of equipment, surface, or other contaminated WPM). Packaged WPM is also at risk of being contaminated if it is stored in an open environment. For example, stone, tile, and heavy machinery parts are often packaged on WPM before being stored together outdoors until an order is received for those goods. During this period, WPM can become contaminated with soil, egg cases (e.g., *L. delicatula*, see: Barringer et al. 2015), or by organisms that shelter in crevices (e.g., wasps, Rau 1930; terrestrial snails, Chen et al. 2016). The risk of packaged WPM bearing contaminating pests can be mitigated by using practices that decrease the risk of it being colonized during storage, including adhering to good yard management practices (IPPC 2020; IMO ILO UNECE 2014) and by post-storage inspection of the packaged WPM.

Packaged WPM is at risk of being contaminated while being prepared for shipment overseas. WPM may encounter contaminating organisms before it is placed into a cargo transport unit (CTU). This process is referred to as 'packing' in the shipping industry. Shipping containers are the most common CTU, but other conveyances such as railcars are also considered CTUs. We use 'container' to refer to CTUs in general. Transferring a container to a conveyance (e.g., a ship) is called 'loading'. WPM can be contaminated by equipment used to assist with the packing or loading process, or by pests already in the container.

Materials are moved from origin to port, loaded onto a ship, and en route in international waters (Fig. 2, Boxes 6, 7, & 8)

As much of the goods traded internationally are transported in ships, most containers will spend time stored at a seaport prior to departure (Kaluza et al. 2010). In a typical scenario, containers are packed and sealed at a manufacturing or production facility or at a warehouse (Box 5), then transported to a seaport via rail or truck (Box 6) where they sit at the shipyard prior to being loaded onto a vessel (Box 7) and shipped (Box 8).

Both unloaded WPM and containers are at risk of external contamination during storage at ports prior to packaging, packing, and loading, especially when stored near exposed lights or on vegetated surfaces. Many insects are attracted to lights (Mazhkin-Porshnyakov 1960; Owens and Lewis 2018) and some may land on or crawl to materials stored near lights, increasing the chance that individuals or egg masses are transported. Even without the influence of light, any time an implement of trade sits outdoors or in open storage near a population of potentially contaminating organisms there is an opportunity for pest contamination. WPM in packed and sealed containers is at risk of contamination if organisms enter the container via cracks or air vents (Koch and Galvan 2008; Lee et al. 2014).

The risk of contamination varies with the length of time the containers are present in the exposed environment, the population density and life stage of the potentially contaminating organism, and the ecological conditions in both close proximity (e.g., grass present in a dirt storage yard) and general vicinity (e.g., forested port environment). If WPM or containers are contaminated prior to departing the port of origin, cross-contamination of WPM or containers may occur en route to the cargo's destination. For example, soil contamination on any packaging material or container can harbor spores, insects, microorganisms, or seeds. During a voyage, these contaminating organisms may mature or become motile and contaminate nearby surfaces.

Once loaded onto a ship, containers, WPM, and break-bulk commodities (i.e., large items like steel beams or heavy machinery) are very difficult to inspect. As such, the process of ship loading is an opportunity for inspection and mitigation of contaminating pests. After loading, however, all container surfaces that are adjacent to a neighboring container or the ship superstructure cannot be visually inspected. This means that less than 10% of the surface area of all the containers is visible on the smallest classes of container ships, and less than 5% is visible on the more commonly used larger ships. Further, only a fraction of loaded surfaces or exposed WPM are low, close, or accessible enough in the stacks to be visually inspected without the use of drones, binoculars, or other instruments. To arrive at these values we assumed a stack of 504 forty foot containers arranged on a small Feeder class ship in a 7L × 9W × 8H block. This configuration has 9% of its total surface area visible for inspection. We further estimated that for the more common Panamax class of container ships, with 3001–5000 containers, only 5% of surface area is visible. WPM used in the securing of break-bulk cargo within the hull of the ship often cannot be accessed at all once loaded due to safety and access issues.

It is the shipper's responsibility to ensure containers are "clean, free of cargo residues, noxious materials, plants, plant products and visible pests" (IMO ILO UNECE 2014) before being loaded on the ship. The CTU code (IMO ILO UNECE 2014) provides guidance and recommendations for the shipper, but these are not mandatory. In the southern Pacific Region the Sea Container Hygiene System is used whereby countries shipping in this region implement a container cleaning regime, which includes cleaning the interior and exterior of containers, and external treatment with insecticide before containers are packed at the loading port. Under this system, the level of inspections of containers from a destination is adjusted using a risk-based sampling approach that takes into account how frequently they are compliant with the regulations (Australian Government 2019).

Ship arrives at a North American port of entry (Fig. 2, Box 9)

Ports of entry are a critical control point for inspection and mitigation of non-indigenous organisms. Arrival at the port of entry presents the first opportunity for non-indigenous organisms to escape and the first domestic opportunity for inspection of shipments by the receiving NPPO. Also, the regulatory status of an organism can change during transport; for instance, a non-regulated organism in the country of origin becomes a regulated pest when the cargo enters the receiving country's waters or crosses a land border.

Before containers and break-bulk cargo are offloaded (Box 10) ships may be inspected by the country in which they are arriving. In North America, ships and cargo are initially under the control of national border protection services: Canadian Border Services Agency (CBSA) in Canada, U.S. Customs and Border Protection (USCBP, housed within U.S. Department of Homeland Security) in the U.S., and Procuraduría Federal de Protección al Ambiente (PROFEPA) in Mexico. These agencies and their associated NPPOs facilitate the flow of trade and are responsible for enforcement activities. Inspection efforts have variable foci, ranging from illegal drugs, human trafficking, contraband items, to biological threats such as those discussed in this paper. Inspection rates and modes relevant to plant-pest protection vary among North American countries and are influenced by various factors (e.g., country, port of origin, port of arrival, time of year, containerized or break-bulk, type of commodity). Decision support systems have also been proposed to aid in deciding to inspect certain ships (e.g., Gray 2016). Ships containing break-bulk cargo and other cargo (such as "roll on, roll off" wheeled cargo, known as 'ro-ro') commonly secured with dunnage are subject to increased inspections in United States ports, as these cargo types have had high rates of non-compliance associated with dunnage in the past (J. Sagle pers. comm.). In Canada and the U.S., these inspections typically happen before the ship is at dock, whereas in Mexico officials may not board ships prior to docking; instead, inspection of the cargo and conveyances is completed in the port yard.

CTUs and break bulk are offloaded and kept in a controlled area (Fig. 2, Box 10 and 11)

Organisms have their first opportunity to escape when materials arrive in their destination country. Those that do escape and successfully establish in a port area can create beachhead populations (Lombaert et al. 2010; Bertelsmeier and Keller 2018) which can act as a source of new species introductions and may potentially lead to the additional spread of unwanted species into surrounding areas. For instance, *Harmonia axyridis* spread to multiple continents from an established beachhead population in North America—not from its native Asia (Lombaert et al. 2010). In the case of *A. glabripennis*, introductions from its native range, beachhead populations, and human-mediated intra-continental movement have all likely contributed to its spread throughout Europe and the U.S. (Javal et al. 2019).

The offloading of containers, ro-ro, and break-bulk commodities at the destination port (Box 10) represents a significant opportunity for organisms to escape. Offloading is also a time for external contamination to be observed, and for indigenous and non-indigenous organisms present in the importing country's port to become newly associated with commodities. If unrecognized infested or contaminated containers or goods sit outside after initial offloading in terminals or yards (Box 11), contaminating organisms may escape into the local environment. For motile organisms (e.g., mobile life stages of invertebrates) this escape may be prompted by any number of abiotic or biotic factors (e.g., a stoppage of movement, completion of dormant period, a change in light or temperature) while sessile organisms or stages (e.g., egg masses, pupae) or soil that contains organisms may be dislodged by the movement of containers and goods within the port or direct exposure to wind or rain. Small organisms associated with WPM within a container can escape otherwise sealed containers via vents, cracks, or along door frames. Loaded containers generally spend 3–5 days in a port (Steenken et al. 2004) but empty containers or dunnage can reside in port for much longer, giving pests additional time to develop or escape. Some containers may also be opened at facilities within the port, providing additional opportunities for pests to escape.

Some proportion of WPM is inspected at all North American ports, but the rate of inspection varies widely according to country of entry, port of entry, country of origin, and commodity. Inspections are often focused on shipments from higher risk origin areas or commodities, similar to the decision metrics for pre-arrival inspections of ships. Work et al. (2005) estimated the annual inspection rate in the U.S. at approx 2% of all WPM. USDA APHIS estimates risk-based sampling currently yields an annual average of 300 wood boring and bark beetles found in wood packing material (USDA 2021). Containers or WPM that are determined to be non-compliant after initial offloading are not allowed out of the controlled port areas in the U.S. or Canada. In the U.S., non-compliant containers or packed WPM may be required to be re-sealed and re-exported at the expense of the carrier by U.S. Customs and Border Protection, or less commonly, non-compliant materials may be destroyed or treated on site. If the dunnage is determined to be non-compliant while associated with a break-bulk commodity, the entire consignment (non-compliant dunnage and its associated commodity) may be rejected and subject to re-export, which may include the vessel. In Canada, the NPPO will order the non-compliant WPM to be removed from the country and may treat material that poses an immediate risk prior to doing so (CFIA 2023). WPM not in compliance with Mexico's standards (SEMARNAT 2018) is not allowed to leave a Mexican port and is subjected to a quarantine protocol (i.e., fumigation) prior to its destruction.

Dunnage removed from ships during the unloading process is often stored within the controlled area of the port. Dunnage represents a significant risk by harboring both infesting and contaminating pests if it is untreated, undertreated, or was handled in a way that allowed post-treatment contamination. As dunnage often has little to no associated chain of custody information, it is more difficult to determine who is responsible for the disposition of non-compliant dunnage. Non-compliant dunnage may be destroyed on site (Box 10), loaded back on a ship and re-exported, treated and allowed to be taken from the port, or illegally deposited within port property.

In North America (and likely elsewhere) illegal deposition of used and untreated dunnage is an increasingly serious issue. Due to these challenges, in 2016 the U.S. revised its regulations to allow for the more rapid destruction of illegally deposited dunnage via incineration at ports of entry (USDA 2017). Since 2008 all shipborne dunnage arriving in Canada has been treated as non-compliant and measures have been taken to treat it as such, regardless of the presence of an ISPM 15 stamp. In 2021 Canada's NPPO recommended allowing dunnage to be reused, as long as it is, or was, rendered ISPM 15 compliant before reuse (CFIA 2021a). In the largest Mexican ports, dunnage that is unloaded is fumigated before its destruction. However, dunnage may remain for considerable periods of time in open-space storage within Mexico's port environs before being destroyed, thereby increasing the risk of organisms maturing to a motile life stage and escaping into the port environs.

Importing non-compliant WPM can have significant logistical and monetary consequences. The U.S. may issue fines or other monetary penalties to shippers of non-compliant WPM and may require the re-export of goods, containers, or conveyances associated with non-compliant WPM. They may also revoke the participation of offending shippers in voluntary programs such as the USCBP Trade Partnership Against Terrorism (C-TPAT) program (USCBP 2022) that speed imports through the inspection process. In Canada, the NPPO can take enforcement actions on violations and issue fines to the entity that is responsible for the non-compliant material. Records of non-compliance are kept by CFIA in Canada, USCBP and USDA APHIS in the U.S., and PROFEPA and SEMARNAT in México. These data are used to develop inspection protocols for commodities, ports, or ships that may present at higher risk of non-compliant material being present.

CTUs and breakbulk leave the port and are moved to distribution centers (Fig. 2, Box 12); WPM is transported with commodities to point of sale or separated at point of distribution (Fig. 2, Boxes 13–16)

Once a container or packaged WPM leaves a port it can be transported by a wide range of conveyances anywhere in the receiving country. During this time there are many opportunities for associated pests to disperse into the local environment. Packed containers and WPM are often stored for variable periods—from days to months—at railyards and distribution centers (Boxes 13, 14, 16, 17). At distribution centers, some containers are opened, unpacked, and the commodities may be unpackaged (i.e., separated from the original WPM). Some goods will remain packaged with their original WPM as they are moved to a retailer (e.g., large appliances, tile, plastic-wrapped palletized bulk goods such as multiple individual sacks of rice). This point in the supply chain presents a high-risk opportunity for pests to leave the unpackaged WPM and disperse into the area surrounding distribution centers (Box 14). Similar to the pest escape context present at ports, the unpacking process introduces potential stimuli for a pest to emerge (e.g., environmental changes such as light, temperature, and humidity) and removes barriers to escape that may have been present in a sealed container; the risk increases with the amount of time spent in a single location.

Distribution centers are located at shipping hubs around the continent, increasing the number of places that could become a first point of introduction (e.g., Krishnankutty et al. 2020) or beachheads for the domestic spread of newly arrived invasive species. Distribution centers and warehouses may be far removed from coastal ports where, historically, most introductions first occurred. However, the storage of large amounts of WPM at distribution centers, or at points of sale for historically high-risk commodities, allows NPPOs and other entities to conduct focused surveillance and target analyses to increase the likelihood of early detection at these types of locations (Rabaglia et al. 2019; Krishnankutty et al. 2020; Morisette et al. 2020).

WPM is separated from goods and stored (Fig. 2, Boxes 16 and 17)

When WPM arrives at a distribution center, the distributors handle WPM and the packed commodities in a variety of ways. They may unpackage the WPM received from the manufacturer and re-package it onto a different unit of WPM (sometimes onto reused WPM; Box 19) or they may leave the commodities packaged and send the WPM to retailers or direct to consumers. Once unpackaged commodities arrive at their final destination they are separated from any remaining WPM and the disposition of any WPM becomes the responsibility of the retailer or consumer (Box 17 and 20). The management and storage of WPM can be unprofitable or inconvenient once it reaches homes or businesses in rural or residential areas, with little incentive for best management practices that could reduce pest-related risks.

WPM separated from goods is often stored for some time prior to the WPM entering a reuse pool, being recycled, or destroyed. During this storage time, as before, the risk of stored WPM becoming contaminated is contingent on local pest presence and the storage environment, and the risk of pest escape from stored WPM is dependent on duration of storage, seasonality, storage area conditions, and other environmental factors.

WPM is disposed of or recycled (Fig. 2, Box 18 and 20) or enters reuse pool (Fig. 2, Box 19)

Pallets, dunnage, crates, spools, and other types of WPM likely each have different rates of entering the reuse markets in North America. One of the most reused types of WPM are wood pallets. The lifespan of a typical pallet includes multiple periods of use across 2 to 10 years (Gnoni and Rollo 2010; Deviatkin et al. 2019; Brad Gething, National Wooden Pallet & Container Association, pers. comm.) and is influenced by factors like its construction, what commodities it has been used to transport, and how many times it was handled during a trip. Pallets and other WPM can be remanufactured or repaired by replacing damaged components (Box 18). In the U.S., recycled and remanufactured pallets make up 42% of the pallet pool (Gerber et al. 2020) but we could find no data on the proportion of the recovery market that is occupied by pallets initially manufactured overseas. Similarly, we found no data on the frequency of reused pallets used for the export of North American goods. To maintain ISPM 15 compliance, pallets that have been repaired or remanufactured must adhere to the manual's specified guidelines on marks and retreatment.

The risk associated with primary infesting pests in repaired and remanufactured WPM could increase if ISPM 15 repair guidelines are not followed and untreated wood is used in the repair process. In the U.S., the majority of repair is done with components from reclaimed pallet pieces so a failure to adhere to repair guidelines would be unusual (Brad Gething, National Wooden Pallet & Container Association, pers. comm.) but it remains possible. Domestic- and international-origin pallets moving into reuse pools could present a risk of transporting invasive pests either domestically, or internationally, if contaminated or infested while in storage prior to reuse (Box 19). As WPM ages over time, different types of pests may be attracted to the material (Naves et al. 2019) so the profile of post-treatment infestation risk is variable. In the U.S. at least one jurisdiction regulates the movement of WPM and other high risk articles to prevent the spread of the non-specific contaminating pest, *L. delicatula* (Pennsylvania Department of Agriculture 2018).

WPM not destined or suitable for reuse is either destroyed in controlled settings (i.e., solid waste facilities, wood processing facilities, or landfills), used in recycling or downcycling markets, or reclaimed (Box 20). WPM that is destroyed may be chipped or otherwise mechanically broken down and sold as other products (e.g., mulch, soil amendment, animal bedding) or enter commercial fiber markets and be manufactured into other wood products (e.g., paper, chipboard, fuel pellets) (Shiner et al. 2021). The final disposition of WPM in these settings likely presents very low pest risk, due to the final dimensions of the wood products being too small to sustain pest development in most cases. Some microorganisms and very minute arthropods- such as fungi, nematodes, or ambrosia beetles- may persist even on chipped or shredded material.

WPM destined for disposal may represent a risk for transporting pests to the immediate area around a given facility; for example, some U.S. regions may be net importers of used WPM for the disposal industry (Shiner et al. 2021). The eventual fate of the fraction of WPM that is neither reused nor destroyed is unknown and the material disappears from the supply chain—this may represent use as fuel wood, conversion to handicraft materials, or other less common final dispositions. There is a paucity of data regarding the final disposition of WPM globally.

Discussion

Managing the phytosanitary risk associated with every piece of WPM used in the international supply chain is a complex and multi-step process involving multiple entities and countries. We have reviewed the various stages in the supply chain to identify distinct areas of phytosanitary risk and determined that the greatest pest risk reduction occurs in the steps up to and including the processing, construction, and full compliance with ISPM 15 treatment. Our review also suggests that the risk posed by WPM after ISPM 15 treatment may be due to; heat or fumigant tolerant organisms surviving treatment, systematic failures in the application of treatments, and post-treatment contamination by contaminating pests. This last cause, however, is shared among WPM and non-wood conveyance material (e.g., plastic, metal).

Several biosecurity tactics, including ISPM 15, are used to help mitigate potential phytosanitary risks (Epanchin-Niell et al. 2021). WPM is a significant pathway by which pests are moved in global commerce and while the implementation of ISPM 15 is documented to have reduced the observed infestation rate of WPM by approximately half, live wood pests are still found in ISPM 15-marked WPM (Haack et al. 2014, 2022; Franklin 2021). No current research exists detailing what proportion of these findings are due to fraud, undertreatment, insufficient treatment level, or other causes. The overall risk of these continuing live interceptions will be unknown until we have a better understanding of their actual frequency and ecological potential to establish and form reproducing populations.

Current tactics used to mitigate risks from WPM in global supply chains are mostly focused on those parts of the supply chain that occur before the commodity departs its port of origin. Much less is known about how WPM is handled in the receiving countries' port and warehouse environments, and how that relates to pest risk mitigation after WPM is in transport to its final destination. Evaluating each step in the WPM supply chain, as we have done here, can identify areas of high risk or high opportunity, where information is lacking and further research, data collection, transparency, or analysis are required, and therefore where to focus future mitigation and research efforts. We discuss these opportunities in the following paragraphs.

The effectiveness of ISPM 15 hinges on treatment levels, compliance, and implementation

The most significant measure mitigating the risk of WPM is ISPM 15. ISPM 15 was first adopted in 2002 and is now implemented by nearly 100 countries. By 2009 there was a measurable correlation between the implementation of ISPM 15 and a 36–52% decline in the percentage of infested WPM intercepted at U.S. ports (Haack et al. 2014). However, a lack of baseline international interception data and the fact that different countries implemented ISPM 15 at different times has continued to limit the ability to quantify declines and make accurate measurement of the change in interception rate over the twenty years since implementation (Haack et al. 2014, 2022). Audits by the European Union concluded that non-treatment and fraudulent ISPM 15 marks were the biggest risks related to wood packaging material, and where full compliance with ISPM 15 occurred it would be effective (EC 2013).

As written and if fully implemented by all 184 contracting parties, the ISPM 15 standard is a powerful tool to mitigate risk, however, the differences in economic, governmental, cultural, and commercial environments among countries create substantial hurdles to achieving the full mitigation of risk. Each contracting party has an obligation and responsibility to administer the requirements of the approved treatments within ISPM 15 at all certified facilities under their authority, and receiving NPPOs may audit the administration of those treatments in the respective source facilities, but the ultimate details of implementation of the treatment requirements is up to the individual NPPO. The hurdles presented by variations in implementation worldwide may be significant enough to create inconsistencies in the effectiveness of treatments, which then generates a significant phytosanitary imbalance between how WPM is both treated at points of origin and how it is inspected and received at the port of entry.

Determining efficacy of treatments under both laboratory and real-world conditions is challenging. Ormsby (2022) has proposed a measure of efficacy and representative taxa against which proposed treatments could be developed and tested for ISPM 15, which could address some of the data deficiencies we have identified. This approach could be combined with an ISPM 15-specific experimental design protocol which would test the real-world efficacy of treatments. Such an approach would give greater clarity by creating an objective measure of phytosanitary treatments that would allow stronger evaluations of plant health protection efforts. Future experimentation aligned with Ormsby's recommended level of efficacy could provide stakeholders with the data necessary to evaluate concerns that conventional heat treatment parameters outlined in ISPM 15 may be inadequate and therefore the direct causal factor driving some of the findings of non-compliance in apparently treated WPM.

The phytosanitary measures described in ISPM 15 do not, by design, provide permanent protection against all types of pests. Much has yet to be learned regarding the incidence and risks associated with pests that become associated with WPM following ISPM 15 treatment. Responding to these risks, if deemed necessary, would also likely require the development and implementation of new policies. ISPM 15 treatment, as conceived, should decrease the pest risk of WPM to a level similar to that of processed wood products (e.g. oriented strand board.) Understanding how and if treated WPM obtains and maintains this of a low risk profile over its entire lifespan and what the level of concern for pests like dry wood borers is to different countries would require additional consideration. Countries can implement management strategies and prescribe handling activities where all WPM, containers, and conveyances may encounter contaminating pests. Research is also required to develop new methods to efficiently treat or retreat WPM that is suspected or known to have become contaminated within the supply chain. These treatments could potentially be applied within the closed environment of a container (e.g., a fumigant, trap, or bait) before it leaves a controlled area.

The success of ISPM 15 relies on the effectiveness and use of approved treatments with complete application. Unfortunately, very little data exists on the frequency of accidental inadequate treatment or intentional treatment fraud to determine how consistently phytosanitary treatments are appropriately applied. In some cases, the consistent application of accepted treatments to WPM may be insufficient such that some heat-tolerant organisms survive and thus would be transported in treated and marked material (Haack et al. 2014; Wu et al. 2017; Eyre et al. 2018; Haack and Petrice 2022). Saprophytic fungi also play a role in suppressing pathogenic fungi that may survive treatments (Uzunovic et al. 2008) though the real world implications of this is not fully understood. The mechanisms underlying the effect of the ISPM 15 heat treatment on the physiological processes of pests are also not understood, nor are the implications of sub-lethal effects on pests that survive treatment. Understanding the implications of these phenomena could lead to better approaches for assessing and predicting risk from potential pest species and in the development of new or modified WPM treatments. An additional challenge to the development of new treatments is the testing needed to determine if those measures are sufficiently effective. Measuring effectiveness has sometimes required exposing thousands, or tens of thousands of insects to the new treatment (e.g., precisely 93,616 insects as in the case of Probit9; Baker 1939), which may not be practical or possible with wood-infesting pests (see Ormsby 2022 for discussion). To address this issue, Ormsby (2022) has proposed that lower numbers of insects can be tested when assessing the effectiveness of treatments against wood- and phloem-feeding insects.

There are also non-biological issues that can impact the effectiveness of ISPM 15. Although it is in violation of the international treaty, infested WPM does enter export chains of custody with fraudulent marks (which falsely indicate the WPM has been treated to ISPM 15 standards; Haack et al. 2014) or lacking in marks altogether (Eyre et al. 2018). This illegal activity may remain undetected as the volume of trade is high while inspection rates are low, and even if inspected, the stamping process is not complemented by additional security or independent confirmation. There is no secondary verification process of a mark's validity or completeness of treatment beyond the presence of a compliance agreement between the treatment facility and the country of origin's NPPO; no chemical or physical indicators are currently known that could be used to provide verification that treatment occurred. As the application of fraudulent marks to WPM is an issue that has trade and legal consequences for trading partners, as well as serious invasive species movement risks, the development of tools or technologies to determine whether marked packaging is non-compliant, whether due to fraud or undertreatment, would be an asset to ISPM 15 implementation.

Issues with fraud and illegal behavior are not unique to WPM. Standardized certification marks are used in other industries (e.g., plumbing fixtures, electrical components, computer parts) where fraud also occurs. Ensuring WPM is ISPM 15 compliant is the responsibility of the NPPO in the country where the WPM originates. Undertreatment—either accidental or purposeful—or deliberate fraud that goes undetected before export use occurs, are serious issues that can result in fines (e.g., NWPCA 2017; USCBP 2004, 2017). Some countries are very stringent with ISPM 15 requirements (e.g., European Commission 2013) yet in North American ports of entry, findings of non-compliance are not uncommon.

Incomplete, insufficient, or improper application of treatment presents financial and legal risk across supply chains; procuring apparently-compliant WPM does not protect private entities from legal, financial, and logistical consequences if that WPM is found to be non-compliant or otherwise infested with live actionable pests. Understanding why these findings occur would better equip the international community to address these issues; effective interventions to reduce non-compliance due to fraudulent markings are different from those necessary to reduce the use of unmarked or undertreated WPM. More studies which assess non-compliance among or across categories of WPM or determine the proportion of findings due to fraud, undertreatment, pest survivorship to treatment, and/or lack of treatment in non-compliant WPM could guide where education, guidance, or policy actions may be needed. Making these determinations with intercepted non-compliant WPM would be difficult and determining true causality would require international cooperation. Research has also not examined the social and economic motivations around compliance and its implications to forest health (Williams et al. in press), or examined how the complex chains of custody common to international supply chains might influence management of WPM.

In some countries, across economic and social spectrums, issues with compliance may arise from a lack of information or infrastructure to properly treat WPM and apply the ISPM mark. Additionally, the resources for verification of treatment facilities, expertise to build facilities, and infrastructure to audit and verify treatments may not be available. In many countries, NPPOs have capacity challenges; for example, Papyrakis and Tascioti (2019) found that communication between treatment facilities and the NPPO is lacking in several African countries, and the ISPM treatment mark and treatment facility verification is not available. In response to this study the IPPC created an expert working group to compile global guidance repositories and create an ISPM 15 implementation manual (IPPC 2017a).

Integrating systems approaches

Our objective was to present a detailed outline of steps involved in the international WPM supply chain as it relates to preventing the entry and spread of forest pests and pathogens into and within North America. A potential future step is to conduct a Hazard Analysis Critical Control Point (HACCP) assessment of this supply chain. HACCP principles are based on using risk assessment to determine how to reduce risk along a production line. Such an assessment could identify how a systems approach might be used to mitigate risks of WPM in supply chains.

Systems approaches consider the combined effects of independent and combined dependent measures on reducing overall pest risk rather than the effect of a single intervention. For instance, harvesting wood for WPM outside the active season for a potential pest and milling that wood in such a way as to remove the tissue where the pest resides are two separate methods that could reduce the specific pest risk for a piece of WPM similar to what a single treatment might accomplish. Without an assessment, the effects of interventions on the pest risk associated with the WPM supply chain are not possible to quantify. Currently, systems approaches are used to mitigate risks of international pest movement for many global commodities, particularly fruits and vegetables (Quinlan et al. 2020; IPPC 2021c) and ash sawn wood (EU 2016). More recently, a standard has been written for the forest product industry and NPPOs with guidance on how to design and implement systems approaches for wood commodities (NAPPO 2018).

One area where systems approaches may be most effective is in reducing risks of contaminating organisms on WPM. Most guidelines for wood pests in commodities address infesting pests closely associated with their host tree species. An added variable present in WPM, packed commodities, containers, and conveyances is pest contamination not specific to host species, nor is the potential for contamination limited to the commodities listed in the consignment. We previously outlined numerous places in the WPM supply chain where contaminating organisms and pests can contaminate WPM. Many terrestrial pests can spread via contamination (Meurisse et al. 2019) and external pest contamination on shipping containers can vary from ~ 0.1% (NZMAF 2006) up to 5% (Gadgil et al. 2000). Recognition of the role containers play in this pathway has resulted in cleanliness programs; e.g., North American Sea Container Initiative (NAPPO 2020), IPPC Sea Container Task Force (SCTF FAO 2008; IPPC 2018; IPCC 2020), and the Australian Sea Container Hygiene System (Australian Government 2019). It is likely that surface contamination of WPM used in similar environments as containers, such as crates and dunnage (Fig. 1C, D), experience a similar range of surface contamination as containers, and thus similar opportunities for mitigation of risk. For instance, one approach to reduce external contamination is to use filters to render lights in storage areas less attractive to insects (Pawson and Bader 2014; Justice and Justice 2016). Implementing a systems approach to reduce contamination of WPM would require additional research to develop a suite of complementary and effective pest mitigation tactics.

Enforcement challenges

Effective enforcement of rules governing the use of ISPM 15 compliant WPM can promote the use of this lower risk material in supply chains. Improving inspection program data collection and conducting targeted studies would help determine the incidence of ISPM 15 non-compliant or untreated WPM, and the incidence of ISPM 15 compliant WPM bearing contaminating organisms (Nodar 2021). Considering this risk is shared regionally, the ideal scenario would be for the U.S., Canada, and Mexico to have harmonized phytosanitary guidelines and enforcement protocols wherever feasible. One approach to begin to answer questions of frequency and types of non-compliance may be to adopt harmonized risk-based sampling regimes. This method identifies and ranks non-compliant imports, then uses that data to identify high risk commodities and predict how many inspections are needed to achieve a desired probability of detection (NAPPO 2021b). Another approach may be to use artificial intelligence methods to increase the effectiveness by marginal or continuous improvement of survey and inspection regimes. To do so would require a large amount of data on the contents of containers, including commodities and their packaging as well as origin and destination, etc. in order to inform a model developed using machine learning approaches. Such a model could be rapidly updated with new interception data and would permit real-time targeting, which would be advantageous when shipments of commodities have one origin but several destinations in different countries.

In comparison to the multi-piece constructed types of WPM such as pallets and spools, we know much less about the risk profile and enforcement of dunnage in North America. Specifically, the propensity of dunnage to harbor organisms that have survived treatment (as it is often much larger by two dimensions than any component piece of a pallet or crate) and the proportion of dunnage that is destroyed after inspection are two significant knowledge gaps. There are no public statistics for the amount of dunnage that arrives at or exists in North American ports, the volume that is destroyed, the length of time between seizure or offloading and destruction, the incidence of findings of non-compliance, or the final destination of offloaded dunnage. This includes dunnage that was loaded in non-North American ports and offloaded by ships before leaving a port in North America, sometimes illegally or without authorization. Canada's NPPO recently reviewed and updated its shipborne dunnage program and created a new risk management document to provide more options for segregating compliant and non-complaint dunnage and to develop disincentives for non-compliant dunnage (CFIA 2021a). In response to increased frequency of enforcement and findings of non-compliance in apparently ISPM 15 compliant dunnage in U.S. ports of entry, some importers have begun exploring options toward additional private inspection at the exporting port, beyond solely requiring the use of ISPM 15 compliant materials (Lovett and Davila 2021).

Risk management of dunnage represents an immense challenge in North American ports. It is therefore necessary to develop phytosanitary guidelines accepted and enforced by all relevant governmental and private authorities that administer and operate in ports. The existing differences among risk management tactics by the three largest North American nations present risks that could be reduced or resolved by harmonizing the approaches to management of dunnage arriving at ports. To prevent the entry of infested or contaminated dunnage into supply chains that lead to North American ports, additional or more stringent phytosanitary requirements or inspections of dunnage could be carried out at the exporting ports to prevent the initial loading of non-compliant pieces. In addition, limited inspections could be conducted on the ships while at sea. If dunnage was determined en route to be non-compliant, its discharge for treatment could be pre-authorized when appropriate, with mitigating measures such as fumigation, heat treatment, or destruction (e.g., incineration, chipping) in authorized facilities within the port areas. The threats to North American ports posed by non-compliant dunnage need to be better managed as part of a holistic approach to risk reduction from all dunnage. Actions that allow for the post-arrival treatment of dunnage could create unintentional incentives for the use of non-compliant materials by shippers. Accidentally creating these unintentional incentives could have the net effect of increasing pest and pathogen presence in dunnage supply chains. One strategy would be to develop third-party approaches to inspecting dunnage before it leaves an exporting port (Lovett and Davila 2021).

A significant part of the enforcement challenge with dunnage is caused by its lack of chain of custody, especially to the commodities it is physically associated with during its primary period of use. Because dunnage is not a multipiece manufactured WPM type, it structurally serves its purpose equally well if cut or salvaged from other wooden materials found at the shipping or loading site. Dunnage is required to be ISPM 15 compliant and should be stored and handled in the same way as other WPM. However, in practice, these use case scenarios allow dunnage or blocking pieces to be added immediately prior to shipping by entities other than the owners or brokers for the commodities being shipped, thereby decoupling the owner of the commodity from the ability to use preferred or proven suppliers of treated dunnage. Dunnage may also be added or loaded by entities other than those responsible for other commodity associated WPM in or adjacent to the same container. There is often no clearly identified responsible party for the presence of a given piece of dunnage (J. Sagle pers. comm.). Without a line of clear ownership for non-compliant dunnage when it is intercepted at the port of entry, enforcement actions and penalties leveled may not impact the most relevant parties.

One incremental improvement to the enforcement challenge around WPM is to use existing programs that incentivise shippers to consistently use fully compliant material, giving the shippers access to streamlined movement of goods. In 2019, the U.S. C-TPAT program added compliance with ISPM 15 for all participating trade partners (USCBP 2020). The C-TPAT program is a voluntary program that provides defined benefits to trade partners who engage in trade security best practices, including adherence and compliance to all relevant international regulations. Canada has two similar programs to C-TPAT in the U.S.: Customs Self Assessment (CBSA 2022a) and Partners in Protection (CBSA 2022b) but they do not have apparent explicit incentives to engage in phytosanitary best practices. Mexico does not have a similar program. The U.S. and Canadian programs may be effective at reducing the amount of unmarked untreated dunnage from entering the supply chain, which could reduce overall pest presence in the supply chain. However, the presence of fraudulently stamped, insufficiently treated, or undertreated dunnage would not be decreased through these mechanisms, as those materials may have apparently valid marks- and thus no visual cue they are in violation of ISPM 15. It is difficult for the users of dunnage to recognize they are purchasing or loading non-compliant WPM if it appears properly marked. Transparency to buyers regarding what facilities have a recent documented history of selling marked dunnage subsequently found to be non-compliant would enable private parties to make informed procurement decisions, which in turn would enable a market-based feedback loop reducing the amount of forest pests entering the supply chain in marked dunnage.

Detecting and removing contaminating organisms on conveyances

Ships, trains, trucks, and other conveyances represent a significant risk of introducing organisms to new locations (e.g., Short et al. 2020). While we focused on WPM in supply chains, we acknowledge these materials are one part of an multifaceted transport system where contamination could occur. WPM is placed into containers, loaded on ships, and transported by airplanes, trucks, and trains. Along the way these conveyances can become contaminated and, in turn, contaminate WPM that was free of organisms when it left its exporting country. Mitigating external contamination on conveyances is challenging, especially during the part of the supply chain where sea containers are transported and stored before being loaded onto a vessel (Fig. 2, Boxes 4 and 5). Mitigating these risks requires the cooperation of multiple trade partners to maintain lower risk yards, equipment, and facilities, as well as visual inspections by trained port personnel. Unfortunately, these facilities and personnel may be subject to constraints on time, staffing, space, and safety protocols in the port environment that can impede best practices and pre-departure inspections.

While there are hundreds of cargo ports in North America, 15 major ports handle 97% of incoming cargo trade on the continent (Mwaniki 2018). Ports may make decisions based on balancing risk and cost effectiveness to determine if inspection and mitigation activities are efficacious and economically sound; these decisions may differentially affect high and low throughput ports due to conveyance volume. Some guidance and recommendations do exist (e.g., IMO ILO UNECE 2014), but they are not mandatory. Research into risk versus cost effectiveness is needed, as models and on the ground testing might help identify areas of improvement. As well, the development of new tools to allow better inspection of more containers and conveyances (e.g., drones, AI-assisted inspection systems) could allow ports of entry to conduct more post-arrival inspections.

Research to document the real-world incidence of contamination in different storage scenarios would be beneficial to determine the propensity of contaminating pests to become associated with WPM, other commodities, and their conveyances. What evidence exists is limited to a species complex of *Lymantria* that are contaminating pests of particular concern (Stewart et al. 2016). Adult *Lymantria* moths are attracted to certain wavelengths of light produced by the bulbs commonly used in the lights at some ports. Studies on the specific wavelength *Lymantria* moths are attracted to (Wallner et al. 1995) led to international guidance on reducing the risk of transporting invasive moth species on shipping containers (NAPPO 2017, 2021a). Other programs require vessels that have been present near infested ports during flight season of some species (e.g., *L. dispar asiatica*) be certified to be free of the insect before departure. Ships that pass inspection are issued certificates prior to departure (Mastro et al. 2021). These programs have proven successful, as 98% of ships arriving to Canadian ports were certified *Lymantria*-free (Mastro et al. 2021). Similar efforts to evaluate the impact of pest biology and ecology and interactions with climate, environment, type of conveyance, or other conditions could lead to the development of similar tactics for other organisms of concern.

Acknowledging that appropriate sanitary measures are not always successfully deployed, the *Lymantria* complex guidance for ships contaminated with egg masses provides clear recommendations for how non-compliant ships should be addressed (NAPPO 2017) via RSPM 33. For example, in Canada, a ship directly contaminated with egg masses may be required to leave the port for cleaning in international waters, redirected to another destination for decontamination, and subject to penalties (CFIA 2021b). Additionally, they may be refused entry for up to 2 years during the risk period for Canada (NAPPO 2021a). Non-compliant wood packaging material on board a ship may be refused entry (USCBP 2021) and in other cases the WPM may be removed and treated (CFIA 2021a).

The contamination and reuse of WPM

The risk of contamination after ISPM 15 compliant WPM treatment can be mitigated by how the WPM is stored. If stored indoors, it will be less likely to be contaminated with pests that contaminate surfaces in the vicinity of host trees (e.g., *L. delicatula*, *L. dispar*). WPM stored outdoors in areas with tall grass is at elevated risk for contamination by terrestrial snails (Cowie and Robinson 2003). WPM stored in the vicinity of bright lights is at elevated risk for contamination by light-attracted pests (Mastro et al. 2021). We know of no research that has examined the likelihood of WPM being infested and/or contaminated during storage or under different storage conditions. Though guides exist for best practices for preventing spread of some organisms on substrates, including WPM (e.g., PDA 2018 for *L. delicatula*), guides are not yet available for all contaminating pests.

Pallets are a commonly reused type of WPM. Damaged pallets can be repaired and reused; the risk of pest movement associated with untreated or contaminated repair components could be problematic if the guidelines in ISPM 15 are not followed. The risk of these repaired pallets that may contain untreated or contaminated components to act as vectors in the domestic movement of non-indigenous organisms has not been investigated. Domestically produced pallets, and pallets moving between countries (e.g., between Canada and the United States), which are not subject to ISPM 15 requirements could pose a risk for movement of pests within a country. For example, in North America, *A. glabripennis* and *A. planipennis* have all undergone substantial movements mediated by cargo transport and other human activities (Shatz et al. 2013; Short et al. 2020). Understanding how and where this type of pest movement occurs is essential for adequate intra-continental management to occur. To address this problem, some countries utilize domestic movement regulations to minimize risk associated with untreated WPM (CFIA 2021c). Pathway analyses for the movement of invasive species via WPM within North America is difficult because not all domestically moved pallets are treated according to ISPM 15 requirements, and if found, the origin of contaminating pests is difficult to trace back. Pallet leasing and pooling may provide information on the history of WPM before it becomes associated with a commodity in domestic distribution.

Plastic pallets and processed wood pallets (pressed, ply, oriented strand, Fig. 5) have been proposed as alternatives to solid wood pallets due to their different risk profile for wood boring and wood infesting organisms. Both plastic pallets and processed wood pallets have different structural properties and reuse profiles than wooden pallets. Plastic pallets require higher energy costs to manufacture and transport than wood (Anil et al. 2020) and require redistribution systems within supply chains, which introduces different logistical and energy costs (Tornese et al. 2018). The use of these WPM alternatives presents a complex set of far-reaching implications, costs, and benefits not explored in this paper, and all remain subject to the same issues relating to the transport of contaminating organisms.

Conclusion

Wood packaging material has been a significant pathway for the introduction of non-indigenous forest pests to North America. ISPM 15 was designed to reduce pest risk from major woodborne pests on this pathway to acceptable levels; however, these pests continue to be intercepted in association with international supply chains and trade activities. These interceptions may occur because of fraud or inadequate application of treatment, failure to treat, pest survivorship of treatment, or other factors that have not been explored. Concrete data on the relationship between these factors and the continued presence of pests in WPM is lacking, and should therefore be an area of renewed research effort. WPM is also a pathway for contaminating pests. This paper follows the supply chain of WPM and identifies areas for improvement and data collection opportunities, and highlights areas in need of additional research which can help improve and inform pest risk reduction strategies for industry, shippers, and NPPOs. Gaps in knowledge highlighted here fall under three major topics: more accurate quantification of different sources of risks, improved treatment application and implementation, and expanded education and training opportunities.

Data that are more accurate or complete would improve risk management models, contribute to more informed management decisions, and benefit both public and private partners. For instance, greater transparency regarding the origin of improperly treated WPM pieces could help improve private procurement decisions and source facility education. Analysis of the many NPPO led strategies and tactics designed to decrease pest risk relies on the collection of pre- and post- intervention data. Unfortunately, many missing data elements have combined to hamper any meaningful analysis of these interventions' effectiveness. These include a lack of baseline data, differences in when various policies were implemented around the world, shifts in those policies, lack of incidence and volume data, and changes in enforcement. Our knowledge of the rates of inspection at ports and at the final destination for cargo are still based on estimates.

Accurate quantification of pest incidence in different types of WPM at each step in the supply chain is still needed, as is the rate or amount of WPM that is reused and/or recycled, and thus exiting the supply chain. More complete datasets could contribute to the analyses suggested by this paper, including systems approaches to reduce pest risk along the WPM supply chain, risk-based sampling approaches to improve biosecurity, and mitigating pest risk associated with different types of WPM (e.g., dunnage). Such analyses would help improve pest risk assessments, guide inspection efforts, and increase the efficacy and efficiency of inspection at specific points in the supply chain.

Despite ISPM 15's universal treatment guidelines, there is still variation in how and if treatments are being applied. We lack data on the proportion of new WPM entering global supply chains each year that is fully compliant with ISPM 15 treatment requirements. Importantly, we also lack data on the causes of the non-compliance found in the remainder of new WPM; fraud and incomplete treatment contribute in unknown proportions to the untreated and undertreated WPM into supply chains. To address and reduce non-compliance, various incentives (e.g., streamlined trade programs) and disincentives (e.g., fines) are in place around the world- but we do not have data showing how they may or may not be contributing to improvements in ISPM 15 compliance rates. Without measures of effectiveness, we cannot focus industry and governmental efforts towards the programs that will most efficiently reduce pest presence in the supply chain. We also lack data on post-treatment contamination rates of WPM – for instance, there is no available research on how often fully ISPM 15 compliant WPM is subsequently contaminated while in use or storage. These data could help develop mitigation strategies to reduce the risk of pests in or on WPM throughout the global supply chain.

Private entities, NPPOs, and tree protection advocates would all benefit from improved education and training of the manufacturers, users, and handlers of WPM. The development of best practices for the handling and care of WPM in manufacturing, storage, use, and recycling facilities could decrease the rate of WPM contamination. Our review highlights several opportunities to increase the knowledge and technical capacity of inspection systems worldwide in the service of global plant health.

Collaborative efforts among industry stakeholders, scientific institutions, government agencies, nonprofit entities, NPPOs and academia are required to increase awareness and address these knowledge gaps, and preventative actions along the supply chain are key to maintaining safe trade. Data on North American pest interceptions, quantifying the number and guilds of organisms moving with trade, as well as the commodities on which they move, would elucidate many of the outstanding questions posed here, including where pest risk is highest and where opportunities to implement interventions to reduce pest risks would be most effective. Combining robust interception and treatment data with knowledge of biological characteristics of pests and a practical knowledge of trade pathways will enable us to better determine how plant pests move in and on commodity-specific pathways and take informed actions to avert their continued entry and potential spread. Interception data, improved traceability, and new science-based tools to evaluate non-compliant WPM are needed to measure and distinguish between fraudulent and accidental under-treatment. This data-driven and science-based approach, combined with an improved understanding of the social and economic factors that will increase proper treatment application and implementation of ISPM 15, will best protect North American trees from infesting and contaminating pests while promoting safe trade using WPM.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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