Annals of the Entomological Society of America, 113(2), 2020, 88–99
doi: 10.1093/aesa/saz051
Advance Access Publication Date: 11 February 2020
Special Collection: Geospatial Analysis of Invasive Insects
Special Collection

Predicting Establishment Potential of an Invasive Wood-Boring Beetle, *Trichoferus campestris* (Coleoptera: Cerambycidae) in the United States

Sindhu M. Krishnankutty,[1,2,7] Kevin Bigsby,[3] John Hastings,[4] Yu Takeuchi,[5] Yunke Wu,[1] Steven W. Lingafelter,[6] Hannah Nadel,[1] Scott W. Myers,[1] and Ann M. Ray[2]

[1]Otis Laboratory, Plant Protection and Quarantine Science and Technology, Animal and Plant Health Inspection Service, Department of Agriculture, Buzzards Bay, MA, [2]Department of Biology, Xavier University, Cincinnati, OH, [3]Plant Epidemiology and Risk Analysis Laboratory, Plant Protection and Quarantine Science and Technology, Animal and Plant Health Inspection Service, Department of Agriculture, Raleigh, NC, [4]Data Analysis Risk and Targeting, Field Operations, Animal and Plant Health Inspection Service, Department of Agriculture, Raleigh, NC, [5]Center for Integrated Pest Management, North Carolina State University, Raleigh, NC, [6]Animal and Plant Health Inspection Service, Department of Agriculture, Douglas, AZ, and [7]Corresponding author, e-mail: sindhu.krishnankutty1@gmail.com

Subject Editor: Jeffrey Morisette

Received 29 March 2019; Editorial decision 9 September 2019

Abstract

Solid wood packaging material (WPM) is widely recognized as a high-risk pathway for transport and potential introduction of wood-boring insects, including longhorned beetles in the family Cerambycidae. These beetles also are occasionally imported in finished wood products, such as furniture and decorative items. A targeted effort to identify wood borers intercepted as larvae in WPM at U.S. ports between 2012 and 2018 revealed that one of the most frequently intercepted species was *Trichoferus campestris* (Faldermann), a cerambycid native to Asia. *Trichoferus campestris* is a pest of quarantine concern in the United States, Canada, and Europe. The establishment risk of this beetle in the United States is high because of its frequent introduction through multiple pathways and its potential to inhabit natural and urban forests as well as agricultural systems. In this study, we compiled port interception and detection data to examine risk based on historical introductions and pathways. We tested whether the intended destination of cargo intercepted with *T. campestris*-infested WPM can be used as a predictor of inland introductions, assuming that individuals of *T. campestris* are likely to be moved through established trade routes between export–import partners. We also developed maps to predict likely areas of introduction and establishment in the United States based on pathway analysis and climate suitability data. The maps will enable informed prioritization of resources in pest surveillance, and may serve as models for other wood borers identified in the WPM and wood products pathway.

Key words: pathway-risk analysis, invasive insect, climate suitability modeling, port interception, risk map

Biological invasions are an important component of human-caused global change. Despite implementation of measures to reduce pathways for biological invasions, introduction of exotic insects and pathogens continues to pose serious threats to natural and managed forests, urban landscapes, and agricultural lands worldwide (Liebhold et al. 1995, Brockerhoff et al. 2006, Moser et al. 2009). Of particular concern are forest insects, especially wood-boring beetles in the families Buprestidae, Cerambycidae, and Curculionidae (including Platypodinae and Scolytinae) (Haack 2006, Haack et al., 2014). Solid wood packaging materials (WPM) such as crating, pallets, spools, and dunnage, are recognized as high risk pathways for transport and potential introduction of wood-boring insects (Allen and Humble 2002, Brockerhoff et al. 2006, Haack 2006, Haack et al. 2014). International Standards for Phytosanitary Measures No. 15 (ISPM 15), which mandates debarking and phytosanitary treatment of wood used for construction of WPM, was implemented to reduce the risk of arrival of pests through unprocessed wood (IPPC 2018). However, wood-boring insects can also be transported in live plants, lumber, and fuel wood. These insects, especially longhorned beetles in the family Cerambycidae, are occasionally also found in finished wood products such as furniture and decorative items, and can emerge as adults years after the item is imported. Even though the risk of transport in these products is generally low, several interceptions of cerambycids were recently reported in manufactured wood products in both Europe and North America (Eyre and Haack 2017).

A targeted effort to identify wood borers intercepted at U.S. ports as larvae in WPM between 2012 and 2016 revealed that several species of cerambycids were intercepted multiple times (Wu et al. 2017), and that one of the most frequently intercepted species was *Trichoferus* (=*Hesperophanes*) *campestris* (Faldermann) (Coleoptera: Cerambycidae) (Fig. 1). Native to China, Central Asia, Japan, Korea, Mongolia, and Russia, it has also been recorded in several eastern European countries (Grebennikov et al. 2010, Pennacchio et al. 2016), and has spread to western Europe by either human-mediated activities or natural dispersal (Dascălu et al. 2013). Interceptions of *T. campestris* in North America and Europe were associated with both WPM and finished wood products of Asian origin, especially from China (Cocquempot 2006, Grebennikov et al. 2010, Maier 2017). Bonsai trees and horticultural stock are also reported as possible introduction pathways for this insect (EPPO 2009). Haack (2006) listed 51 port interceptions of individuals in the genus *Hesperophanes* and two interceptions of individuals in the genus *Trichoferus* in a summary of data between 1985 and 2000 compiled from the United States Department of Agriculture (USDA) Animal and Plant Health Inspection Service (APHIS) Pest Interception Database (internally referred to as the Pest ID or Agricultural Quarantine Activity System [AQAS] database). USDA pest risk assessment reports of wood-boring insects associated with solid WPM and wood products, particularly from Asia (Wallenmaier 1982, Cavey 1998), recognized the genus *Trichoferus* and *T. campestris* (listed as *Hesperophanes* and *H. campestris*, respectively) as having quarantine significance based on their frequent interception and ability to attack living trees. Frequent interception of *T. campestris* at U.S. ports suggests the likelihood that some individuals may have escaped detection and entered the country in uninspected cargo or WPM.

The first detection of adult *T. campestris* outside a quarantine facility in the United States was near a warehouse in New Jersey in 1997 (Bullas-Appleton et al. 2013). Adults were later collected in a residential area in Montreal, Canada in 2002 (Grebennikov et al. 2010). Due to its quarantine status, *T. campestris* is targeted in the United States by exotic wood borer and bark beetle surveys for members of the families Buprestidae, Cerambycidae, and Curculionidae conducted by the Cooperative Agricultural Pest Survey (CAPS), a joint Federal and State Program. Adults of *T. campestris* have been trapped in multiple states since 1999, including Colorado (2013), Illinois (2009), New Jersey (2007, 2013), New York (2014, 2016–2018), Ohio (2009, 2017–2019), Pennsylvania (2016), Rhode Island (2006), and Utah (2010, 2012–2019) (Ray et al. 2019, A. Ray, unpublished data). *Trichoferus campestris* populations are now considered established in Illinois, Utah, and Wisconsin (CERIS 2019, Ray et al. 2019).

Trichoferus campestris seriously damages timber, lumber, and dry wood (including wooden buildings) in Japan and China (Iwata and Yamada 1990, Xinming and Miao 1999). Its host range is broad, comprising at least 40 genera of conifers and hardwoods, and it may even develop in herbaceous plant species (Iwata and Yamada 1990, EPPO 2009, Bullas-Appleton et al. 2013, Dascălu et al. 2013). In Utah, *T. campestris* infests medium to large peach and cherry trees in commercial orchards (Ray et al. 2019) and was recently found to infest both living and weakened sections of trees (B. Wang, USDA APHIS, personal communication). In Ontario, Canada, a small number of *T. campestris* adults were reared from a moribund Norway maple, *Acer platanoides* L., which the authors concluded was likely killed by a fungal pathogen (Bullas-Appleton et al. 2013). Despite the pest information available on the species, gaps in knowledge still exist about its full host range and potential for economic damage (Ray et al. 2019).

The invasive capacity of *T. campestris* is likely compounded by multiple pathways into urban areas and distribution centers linked to U.S. ports, and its potential to inhabit a diverse range of forests (natural and urban) and agricultural lands (fruit orchards). Early detection initiatives in invasive species management that include surveillance and monitoring often operate with limited resources, and therefore, must be carefully planned (NISC 2003). Maps that can predict entry points and establishment potential of a damaging invasive species can enable informed prioritization of resources toward high-risk areas. In this study, we aimed to predict the establishment potential of *T. campestris* in the United States based on the available data, namely, port interceptions, inland detections, climate suitability, and commodity pathway information. The methods developed here are expected to apply also to surveillance for other wood-boring pests found in the WPM pathway.

We also explored whether the intended destination of cargo intercepted with *T. campestris* in the WPM can serve as a predictor of inland introductions. Although insects included in the present study were intercepted and removed from the pathway, information about intended destinations can help us understand where *T. campestris* is likely to be introduced. This approach assumes that import–export partners engage in long-term trade of similar cargo with similar WPM. Because *T. campestris* is frequently intercepted in quarantine (e.g., Wu et al. 2017), some WPM included in these shipments may have been infested with *T. campestris* but escaped detection. Concurrence between intended destinations and localities where *T. campestris* was detected would support the use of intended destinations as potential proxies for realized destinations.

The specific objectives of this study were, therefore, to 1) compile historical interception records of *T. campestris* at U.S. ports of entry and detections at inland locations, 2) to predict areas of *T. campestris* introduction and establishment in the United States based on pathway analysis and climate suitability data, and 3) to determine whether the intended destination of cargo intercepted with *T. campestris*-infested WPM can be used as a predictor of inland introductions.

Materials and Methods

Port Interception Data

The USDA APHIS Pest Interception Database (Pest ID) records in the AQAS were queried for port interceptions of all taxa of *Trichoferus* and *Hesperophanes*. Port interception forms are compiled into the database, providing records of port of entry, interception date, country of origin, inspected commodity, inspected host (e.g., wood product, WPM, or baggage), number and life stage of live specimens detected, and taxonomic determination. Data on specimens intercepted after December 2016 were retrieved from the Agricultural Risk Management (ARM) system, a new database that replaced interception data entry in Pest ID by the U.S. Department of Homeland Security Customs and Border Protection (CBP) and the USDA APHIS plant inspection stations. Most of these records were limited to genus-level identification.

Species-level identifications were made during a survey of wood borers in WPM between April 2012 and January 2018. We obtained and identified specimens of *T. campestris* that were intercepted alive at selected U.S. ports of entry through a collaborative study between CBP and USDA APHIS (see Wu et al. 2017 for details). Specimens intercepted as adults were identified to species

Fig. 1. Dorsal habitus of *Trichoferus campestris*.

level by national identifiers at the USDA Systematic Entomology Laboratory (Beltsville, MD). Immature specimens were shipped alive to the USDA APHIS Plant Protection and Quarantine Science and Technology insect containment facility at Otis Laboratory (Buzzards Bay, MA) for rearing to the adult stage. Following emergence, adults were euthanized and sent to the Systematic Entomology Laboratory for identification. Larvae that died were preserved for molecular analysis and identified through DNA barcoding; sequences were obtained at Otis Laboratory for all specimens possible, regardless of life stage reached. Voucher specimens are maintained at the USDA APHIS Otis Laboratory.

Inland Detections in the United States

Inland detection records of *T. campestris* within the United States were compiled from several sources: literature (Cocquempot 2006, Grebennikov et al. 2010, Bullas-Appleton et al. 2013), the Pest ID databases, the National Agricultural Pest Information Services (NAPIS) (https://napis.ceris.purdue.edu/), and records available to one of the authors (S. W. Lingafelter). The Pest ID system was queried for inland detections of all taxa of *Trichoferus* and *Hesperophanes*.

Cargo Destinations as Predictors of Inland Introductions

To link the risk of *T. campestris* introduction firmly to the WPM pathway, a correlation must be shown between inland locations where individuals of *T. campestris* were detected and the destinations of WPM infested with *T. campestris*. Such data are lacking, however, because, by definition, the intercepted packaging materials have been prevented from reaching their destinations. An alternative correlation was sought, therefore, between inland locations at which *T. campestris* was detected and the *intended* destination of intercepted WPM that harbored live individuals of this species. Although destination postal codes were available in the databases for cargo with intercepted WPM, we scaled up the destination of cargo to county level instead of postal code- or city-level to match the scale at which detections are mapped in the CAPS website (CERIS 2019). Destination postal codes were available in the AQAS Emergency Action Notification (EAN) system and Pest ID databases. Counties that represented intended destinations for cargo with WPM infested by *T. campestris* are referred to from here on as intended-destination counties (IDCs).

Climate Suitability Modeling

Regions in North America suitable for *T. campestris* establishment were determined using a region-matching algorithm in CLIMEX Version 3 (Sutherst et al. 2007). This tool is best used when the biology of the pest is not well known (Venette 2017). *Trichoferus campestris* distribution in native and non-native regions outside North America was used to identify areas within North America with similar climatic conditions. Where possible, we selected distribution points (Supp Table S1 [online only]) that could be confirmed through specimen data labels or published literature, but knowledge of the distribution of *T. campestris* in its native range (e.g., China and eastern Russia) is limited and, thus, necessitated rough estimates based on the geographical centers of provinces or districts (Supp Table S1 [online only]). Data on the precise location of *T. campestris* in Canada were not included in this analysis.

CLIMEX Match Climate evaluates climate patterns based on temperature, precipitation, soil moisture, and relative humidity (RH). As *T. campestris* spends most of its time in wood, we assumed that soil moisture has a negligible effect on its life cycle. Preliminary laboratory trials revealed that exposure to low (yet > 0°C) temperature is required to induce pupation in *T. campestris* larvae (H. Nadel, unpublished data). Thus, in this assessment, only temperature and precipitation patterns were evaluated as climatic conditions. Even if the direct role of RH in the development *of T. campestris* is not known, it is indirectly accounted for, as RH is correlated with temperature and precipitation.

The model calculates a Composite Match Index (CMI) ranging from 0 to 0.9, indicating similarity of climatic conditions with that in known pest localities. The U.S. distribution data of established populations was subsequently used to determine the lowest presence threshold value. CMI greater than 0.7 is considered a significant climatic match, likely to be suitable for a breeding population (Robertson et al. 2008, Kriticos 2012, de Morais et al. 2013, Phillips et al. 2018).

Entry Locations

A key limitation to risk analysis for wood-boring beetle infestations in WPM is that the final destination of these pests or commodities is mostly unknown. To better understand these patterns, we determined the types of commodities often associated with WPM and the types of businesses that import these commodities. We then mapped the location of these businesses using a proprietary dataset provided by D & B Hoovers (Short Hills, NJ; http://www.hoovers.com/, accessed on 15 February 2018), an analytics company that compiles information about businesses throughout the United States. Finally, we combined all of these locations using the Multi-Attribute Frontier method into a continuous surface that displays a likelihood score for WPM material arriving at that destination. A basic assumption for this study is that risk resulting from trade activity is directly correlated with risk of movement of nonintercepted pests within the wood.

WPM Commodities, Associated Industries, and Propagule Pressure

The types of cargo that were frequently associated with emergency action notifications for wood-boring beetles, or WPM that was not compliant with ISPM 15 regulations at ports of entry, were determined from the EAN database. We then cross-referenced this information to the types of industries (using the North American Industry Classification System [NAICS]) that were likely to import these commodities. We were constrained to 250,000 records of businesses within these industries, and therefore used a subset of the data available through D & B Hoovers (see above). The primary industries were those engaged in sales of stone, cement, ceramic tile, metal, machinery, wood products (manufactured items such as furniture, decorative items, new pallets, etc.), and businesses involved with wood fuel processing, log hauling, logging, and milling of saw lumber (complete list and NAICS codes are in Supp Table S2 [online only]). These data provided information on the revenue and facility size of a business. We assumed these attributes correlated with the volume of commodities and therefore the amount of WPM that would enter any single facility, and were, therefore, good proxies for the propagule pressure of *T. campestris*. The revenue of the business was the preferred measure, but when that was unavailable, we used facility size (floor area). We mapped the locations of the businesses using their coordinates. Business locations were provided as point locations that needed to be aggregated as a continuous surface. We did this by summing the values of revenue or facility size for each point in a 10 km grid cell.

Creating Risk Scores Using Multi-Attribute Frontier

The Multi-Attribute Frontier (MAF) method combines the values from multiple data elements, for example, businesses that import and distribute commodities with WPM, into a single risk or likelihood score. MAF first plots the rank-transformed values of each data element in multidimensional space where each dimension or axis corresponds with a single data element. MAF can be used on data with different units (e.g., revenue or facility size), but the values are transformed into relative ranks. The coordinates of each point correspond with the rank values of the data elements, creating a point cloud with the same number of axes as data elements. The final score is computed by finding the multiattribute frontiers in the point cloud of ranks, which can be done with a convex or a concave approach (Yemshanov et al. 2013).

In the MAF, we used a convex, or more conservative, approach that results in a greater number of grid cells with a high score. Grid cells with the highest rank values were determined by comparing all grid cells in multiattribute space and delimiting a boundary around the grid cells with the highest scores. This boundary in the point cloud is one point deep and essentially represents a multiattribute efficient frontier (Fig. 2). All points on this boundary are assigned a score of one, reflecting the highest score, and then removed from the dataset. The next boundary or efficient frontier is then generated from the remaining points using the same approach and assigned a score of 2 (the second highest score). This process continues until all points in the multicriterion dataset are assigned a score and removed from the point cloud. The scores are then rescaled linearly to a 0–1 range, so that the values close to one depict the highest score and those close to zero the lowest score. MAF has been applied in studies that assign a single score to geographic areas to determine the likelihood of pest spread or to prioritize surveillance allocation resources (e.g., Yemshanov et al. 2013, Yemshanov et al. 2014) and in other mapping applications whose goal is to create a single map displaying a combination of factors (e.g., Yemshanov et al. 2015, Hastings et al. 2017). MAF does not average; rather the components of a multicriterion dataset are depicted as points in multicriterion space that are ranked and then selected for a particular score. MAF works well in situations lacking the data on a pest that would be required to create a more specific epidemiological spread model.

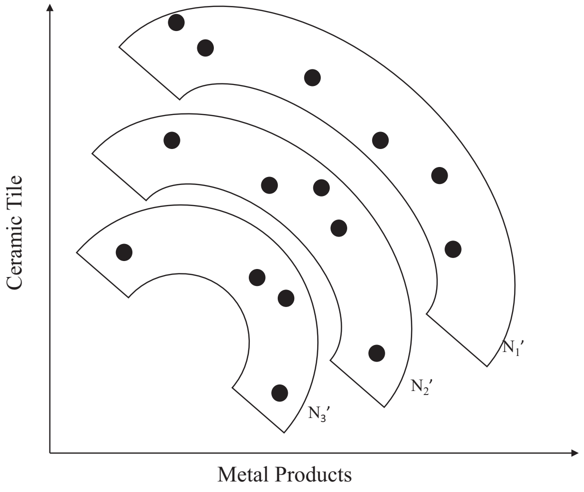

Fig. 2. Multi-Attribute Frontier. Example in two dimensions showing two data elements modified from Yemshanov et al. (2013). Each risk element is assigned an axis in multidimensional space. Along each axis the rank values are plotted, generating a two-dimensional point cloud. MAF is used to first find the points furthest from the axis origin, the highest ranks, N$_1$′. These points are removed and the process is repeated to delineate the second frontier, N$_2$′ and then the third frontier, N$_3$′. This process is repeated until all points are removed from the point cloud and all ranks are found.

Because fewer businesses are classified as importers relative to the number of recipient domestic businesses that represent final destinations, we used a two-stage MAF approach to ensure equal weight to both. The first stage included two separate MAF models, one for importers and another for final destinations. In the first stage, we estimated the risk scores for all importer data elements independently from domestic data elements. The outputs of the first stage, which reflect the independent risk scores, were then used in the second stage to determine a risk score that was evenly balanced between these two groups.

Development of an Optimal Map Using Both CMI and WPM Scores

To prioritize areas for pest surveillance, we used data on the locations where *T. campestris* has been established or detected multiple times in the United States, in combination with the CMI and WPM entry maps. Both the CMI and WPM maps are best guesses for where *T. campestris* could establish, but surveillance resources for *T. campestris* are sparse and surveys cannot be conducted in all areas. To create an optimal map that balances sparse resource availability with a potentially vast area suitable for establishment and entry, we first created multiple maps displaying a more selective range of scores. We then determined the value of the CMI and the WPM score in areas where *T. campestris* is either established or detected multiple times in the United States. The detection records used in this method to assign WPM scores are listed in Table 2. We used this information to determine the optimal score for the CMI and WPM to help limit areas where surveillance resources could be deployed.

Results

Port Interceptions

The Pest ID system listed 60 separate interceptions of *T.* campestris (including entries of *Hesperophanes campestris,* the previously used name for the species by U.S. taxonomists), 12 *Trichoferus* sp. and 75 *Hesperophanes* sp. (Supp Table S3 [online only]) at 15 U.S. ports (Fig. 3) between 10 June 1997 and 24 November 2017. Fifty-two (88%) of 60 interceptions were found in WPM, four in wood products, one in passenger baggage, and the remaining three in unidentified products (Supp Table S3 [online only]). Thirty-four (65.4%) of the intercepted WPM displayed ISPM 15 marks purporting to comply with pre-export phytosanitary treatment. The majority of infested WPM (Fig. 4) was associated with metal (26.7%) and stone products (25%) (Supp Table S3 [online only]). China was the origin of 81.6% of the intercepted shipments with infested packaging and wood products. Most interceptions (18) occurred at the port of Seattle, WA, followed by Long Beach, CA (11). Of 52 interception records in infested WPM, 48 were from WPM with cargo arriving at maritime ports, while others were recorded at rail, air, and land-border ports.

Inland Detections in the United States

Adults of *T. campestris* were detected in 30 counties of 17 states in the United States and Puerto Rico between 1992 and 2018 (Supp Table S4 [online only], Fig. 3). Individuals were detected in both residential and commercial properties, in parks, and in agricultural areas. Of 30 detection counties, four in three states (Cook, DuPage, IL; Salt Lake, UT; Milwaukee, WI) are listed by CAPS as having established populations (CERIS 2019).

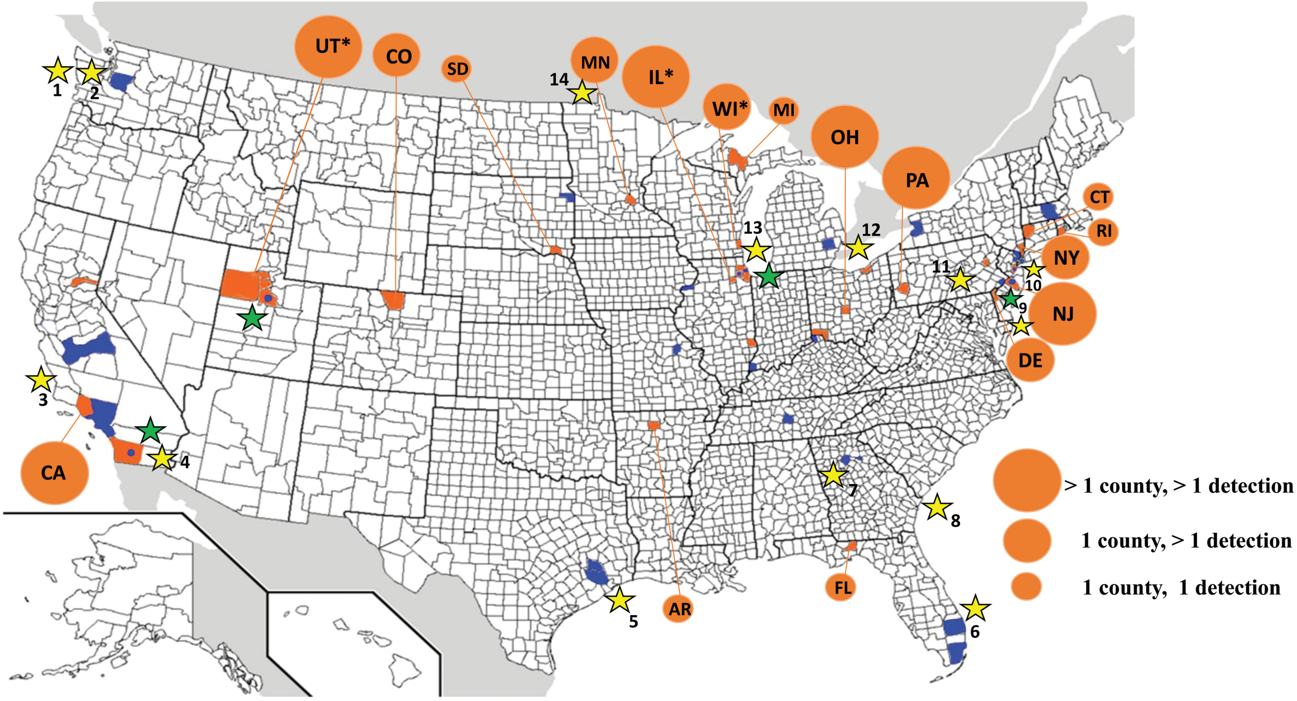

Fig. 3. Map of U.S. counties showing inland detections (orange), intended destinations (blue) of WPM and wood products infested with *Trichoferus campestris*, and ports of entry where the species was intercepted in WPM and wood products (yellow stars). Counties with records of both inland detection and intended destination are indicated as blue dots in orange counties and highlighted by green stars. Numbers next to yellow stars correspond with ports as follows: 1—Seattle, WA, 2—Tacoma, WA; 3—Long Beach, CA, 4—Otay Mesa, CA; 5—Houston, TX; 6—Port Everglades, FL; 7—Atlanta, GA; 8—Savannah, GA; 9—Baltimore, MD; 10—Mullica Hill, NJ; 11—Philadelphia, PA; 12—Detroit, MI; 13—Chicago, IL; 14—International Falls, MN. The beetle was also intercepted at the Carolina Plant Inspection Station in Puerto Rico (not shown). Asterisks indicate states with established populations - Cook, and DuPage Counties, IL; Salt Lake County, UT; Milwaukee County, WI.

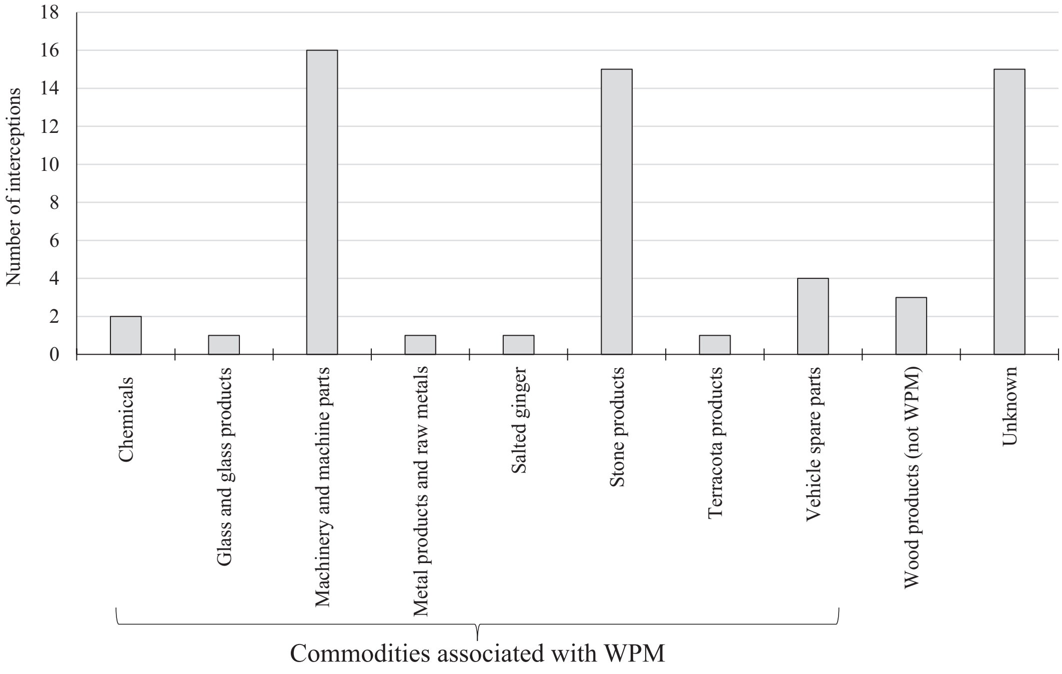

Fig. 4. Frequency distribution of commodities and wood products intercepted with *Trichoferus campestris* at U.S. ports of entry between 10 June 1997 and 24 November 2017. Sources: Pest ID, EAN, and ARM databases.

Cargo Destinations as Predictors of Inland Introductions

Data on IDCs and inland detections indicate that intended destinations provide useful proxies for data on realized destinations of infested WPM and have some predictive value. Data compiled from Pest ID revealed 27 IDCs for *T. campestris*-infested WPM. Fifteen of these IDCs were surveyed by CAPS. Of these 15 counties, 3 (23%) had CAPS detections (Table 1); these are now listed as established

Table 1. List of counties recorded as intended destinations for cargo with WPM infested by *Trichoferus campestris*, and records of inland detections in those counties

Intended destination county (IDC), State	CAP survey results in same IDC (2007–2018)	Detections other than CAPS in same IDC	Detections in neighboring county	Detection summary (same IDC or neighboring county)
Burlington, NJ	Not found	Yes, in wood product		Yes (same county)
Cook, IL	Found and listed as established in 2014	-	-	Yes (same county)
Du Page, IL	Found and listed as established in 2013	-	-	Yes (same county)
San Diego, CA	Not found	Yes, in wood product	-	Yes (same county)
Salt Lake, UT	Found in 2013, 2014, 2015, 2016; listed as established in 2013	-	-	Yes (same county)
Bergen, NJ	No survey	-	Yes, in Westchester, NY	Yes (neighboring county)
Boone, KY	No survey	-	Yes, in Hamilton, OH	Yes (neighboring county)
Los Angeles, CA	Not found	-	Yes, in San Diego, CA, in wood product	Yes (neighboring county)
Orange, CA	Not found	-	Yes, in San Diego, CA, in wood product	Yes (neighboring county)
Philadelphia, PA	Not found	-	Yes, in Burlington, NJ, in wood product	Yes (neighboring county)
Queens, NY	Not found	-	Yes, in Westchester, NY	Yes (neighboring county)
Fresno, CA	No survey	-	-	None
Miami-Dade, FL	No survey	-	-	None
Palm Beach, FL	No survey	-	-	None
Clarke, GA	Not found	-	-	None
Gwinnett, GA	Not found	-	-	None
Rock Island, IL	No survey	-		None
Worcester, MA	Not found	-	-	None
Oakland, MI	Not found	-	-	None
Boone, MO	Not found	-	-	None
Montgomery, MO	No survey	-	-	None
Erie, NY	Not found	-	-	None
Grant, SD	No survey	-	-	None
Rutherford, TN	No survey	-	-	None
Harris, TX	No survey	-	-	None
Montgomery, TX	No survey	-	-	None
King, WA	No survey	-	-	None

populations (CERIS 2019). Two additional, non-CAPS, detections were made in wood products at two IDCs. Thus, *T. campestris* beetles were detected in five (18%) of 27 IDCs (Table 1). Beetles were also detected in counties neighboring six IDCs in which surveillance but no detection was made (Table 1). No beetles were detected in or near 16 IDCs (Table 1). Thus, of 27 IDCs, a minimum of 11 (40%) have had introductions, establishments, or detections in neighboring counties.

Climate Suitability Modeling

The CMI map (Fig. 5), created with limited data using the CLIMEX Match Climate model, indicates that much of the continental United States, northern Mexico, and southern Canada are climatically suitable for *T. campestris* establishment. Only Florida, southern Texas, and high-elevation and coastal regions of Western United States and Mexican states are predicted as unlikely locations for establishment of *T. campestris*.

Entry Locations

The MAF approach, incorporating final destinations of WPM (with cargo) and wood products, along with trade types and business economic indicators, predicted that risk of entry by *T. campestris* from foreign locations is generally highest at major transportation hubs and metropolitan areas (Fig. 6). The model applies to volume or frequency of trade most likely to be associated with WPM.

Development of an Optimal Map Using Both CMI and WPM Scores

To prioritize pest surveillance in areas at highest risk for entry or establishment of *T. campestris*, 16 reference locations were selected where the species is established or more likely to become established in future based on multiple captures within a county or captures in traps in residential or commercial landscapes (Supp Table S4 [online only]). WPM entry-risk scores in these reference localities, henceforth referred to as detection localities, ranged from 0.16 to 1.0. Area within the United States corresponding to each WPM score was calculated, and the numbers of detection localities included within it were counted. Low WPM scores captured a greater proportion of the 16 detection localities but encompassed a greater area compared with high scores (Table 2). WPM scores of 0.16–1.0 included 7.8% of total U.S. area and included all 16 detection localities (Fig. 7). At a WPM score of 0.41–1.0, corresponding U.S. land area was reduced to 3.38% but three of 16 detection localities were missed. At a WPM score of 0.75–1.0, land area was reduced to 1.08% but six detection localities were missed. Areas in the United States that are more climatically suitable for establishment of *T. campestris* had CMI scores of 0.8 and above. Thus, based on both CMI and WPM scores, the resulting map (Figs. 8 and 9, individual maps are in Supp Fig. S1 [online only]) included all areas where the WPM score was greater than 0.41 and the CMI value was at least 0.8. We can predict, therefore, that narrowing surveillance to 3.4% of the area of the continental United States would capture more than 80% of the localities where *T. campestris* could become established, whereas narrowing surveillance to 1.1% of land area would capture only about 63% of potential localities.

Discussion

Risk of *T. campestris* entry and establishment in the United States was estimated by a number of approaches, including 1) locations of

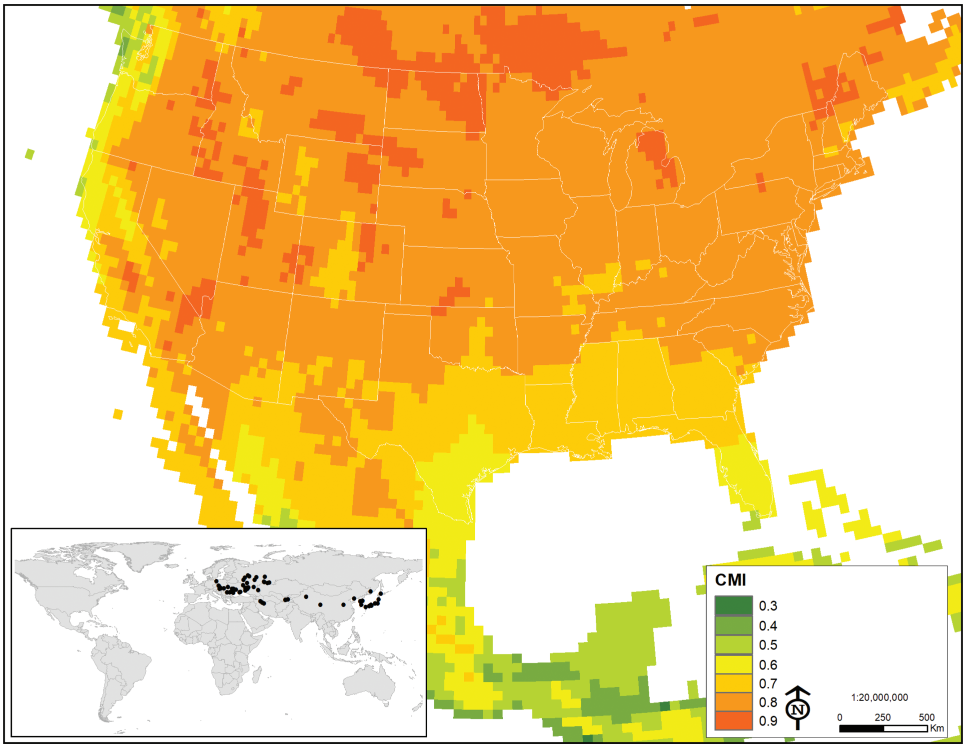

Fig. 5. Composite Match Index (CMI) map determined with the CLIMEX Match Climate model to indicate areas in the United States climatically suitable for establishment of *Trichoferus campestris*. Areas with significant match are indicated in orange and red (CMI scores > 0.7).

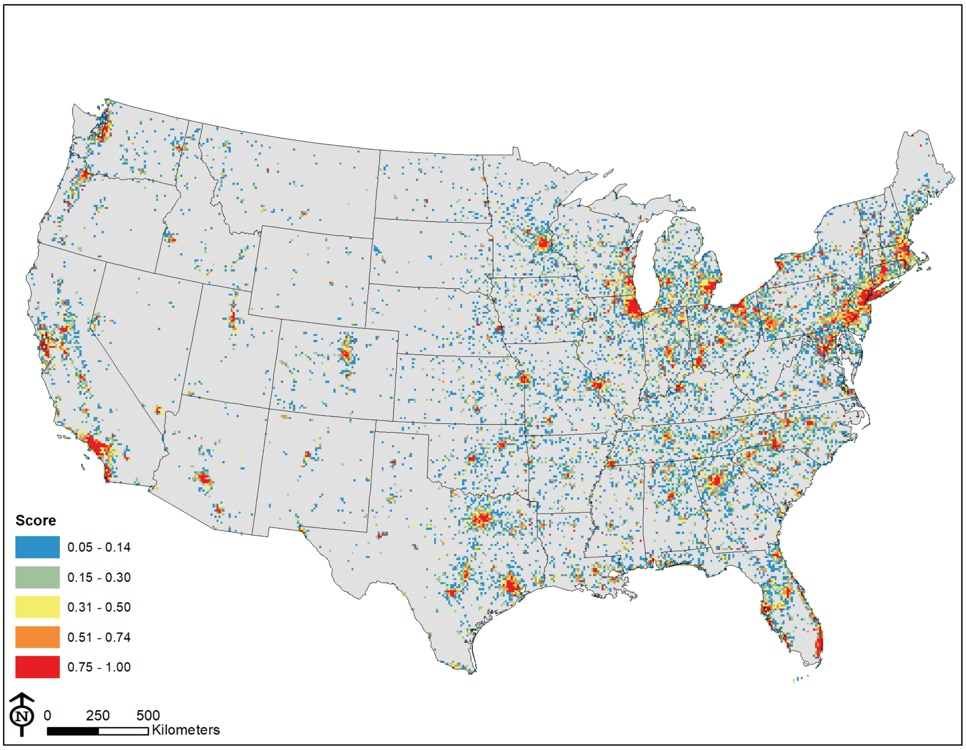

Fig. 6. Entry-risk map for *Trichoferus campestris* built using the Multi-Attribute Frontier method. The attributes are based on business types and locations, and revenue or size of facilities associated with solid wood packaging and with wood products. High scores correspond to high risk of entry.

commercial import and distribution centers experiencing frequent arrival of WPM from ports of entry, 2) points of introduction predicted by intended destinations of cargo intercepted at U.S. ports associated with WPM harboring *T. campestris*, and 3) areas climatically suitable for the insect in North America, based on matching climates in North America with suitable climates throughout the

Table 2. Area within the United States calculated from map grid cells with same WPM entry-likelihood scores and the number of reference locations and detections of *Trichoferus campestris* that occurred in the area corresponding to each score

	Entire US 10 km cells	WPM > lowest value	WPM > 0.16	WPM > 0.33	WPM > 0.35	WPM > 0.41	WPM > 0.56	WPM > 0.57	WPM > 0.76
U.S. area (km)	9,674,000	1,805,100	753,800	412,900	389,400	327,100	211,300	205,400	104,600
No. of *T. campestris* detections encompassed in this area	16	16	16	15	14	13	12	11	10
No. of *T. campestris* detections that would have been missed	0	0	0	1	2	3	4	5	6
Percent United States to be surveyed	100	18.7	7.8	4.3	4.0	3.4	2.2	2.1	1.1

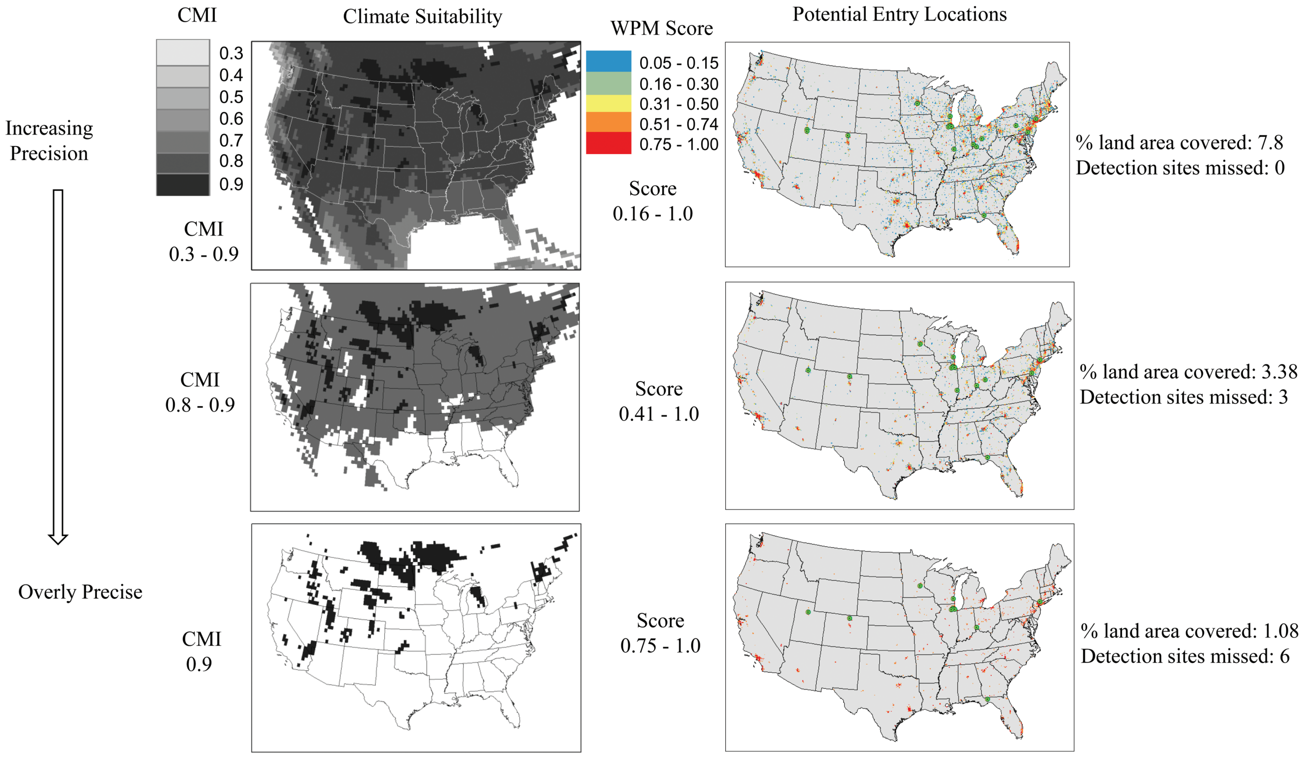

Fig. 7. Maps displaying likelihood-risk scores under selected ranges of CMI (0.3, 0.8, 0.9) (left) and WPM entry (0.16, 0.41, 0.75) (right). Green circles on entry-risk maps (right) indicate locations where *Trichoferus campestris* is either established or more likely to become established in future based on multiple captures within a county or captures in traps in residential or commercial landscapes.

distribution of the insect in its native and non-native ranges in Asia and Europe. Locations of inland detections and established populations provided a preliminary means of validating the approaches used here. Intended destinations of cargo associated with infested WPM often coincided with detection or establishment of *T. campestris* within counties or adjacent counties, conferring some value to intended destination as a correlate of risk. Historical introduction records and pathway data can aid prioritization of quarantine and surveillance efforts for species unintentionally transported via goods. Port interception records (Supp Table S3 [online only]) suggest that this species has been repeatedly introduced through two main pathways: WPM and wood products. Data gathered on port of origin of WPM and wood products infested with *T. campestris* indicate that China is the major driver behind the frequent introductions of this insect into the United States (Supp Table S3 [online only]). We must point out that the number of interceptions recorded at ports of entry are nonrandom due to targeted inspection based on a history of noncompliance with ISPM 15 by exporting companies and their WPM-treatment facilities, or by particular exporting regions or certain commodities that are historically associated with wood borer infestation (Haack 2006, Eyre and Haack 2017, Eyre et al. 2018).

It is clear, based on inland detection records (Supp Table S4 [online only]), that this species is likely to be found near human-associated habitats such as wood recycling sites, pallet and dunnage yards, warehouses, and residential and commercial landscapes. Final destinations for wood products and for cargo associated with WPM are concentrated in urban areas, especially in areas east of the Mississippi River and in major cities in the western United States. These are predicted to be at greatest risk for entry by *T. campestris*. Commodities associated with WPM containing live *T. campestris* originated mainly from China (Supp Table S3 [online only]), and consisted primarily of machinery, machine parts and stone products (Fig. 4). This likely reflects the volume of trade in these products, but also supports a link between heavy commodities and higher infestation

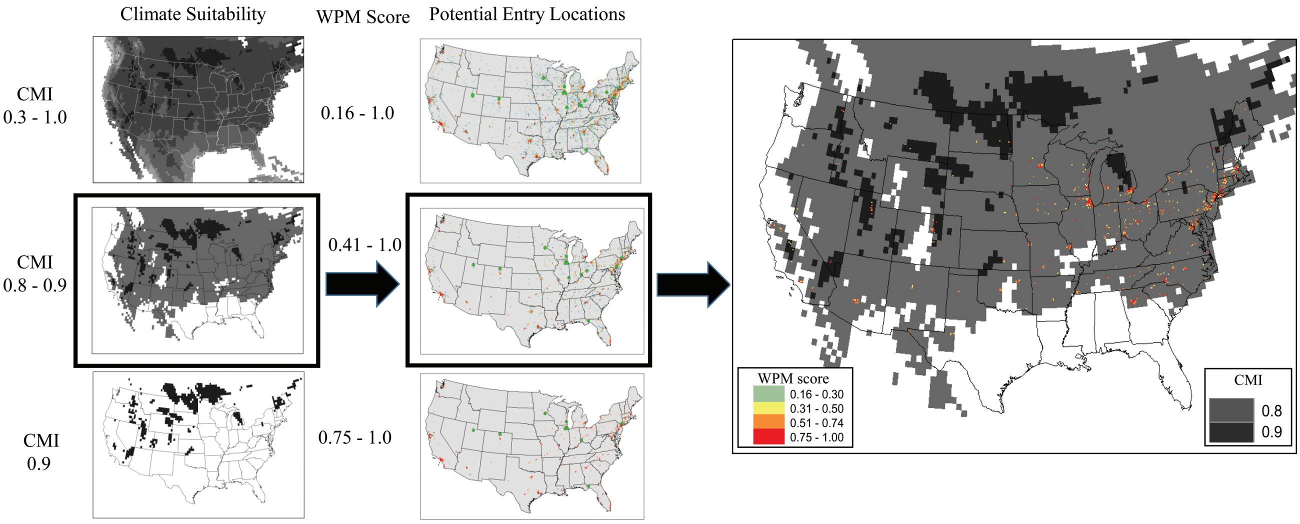

Fig. 8. Flow chart showing how optimal map of potential establishment area of *Trichoferus campestris*, is created by combining entry-likelihood at final destinations of WPM and wood products, with climate conducive for the beetle's development and survival.

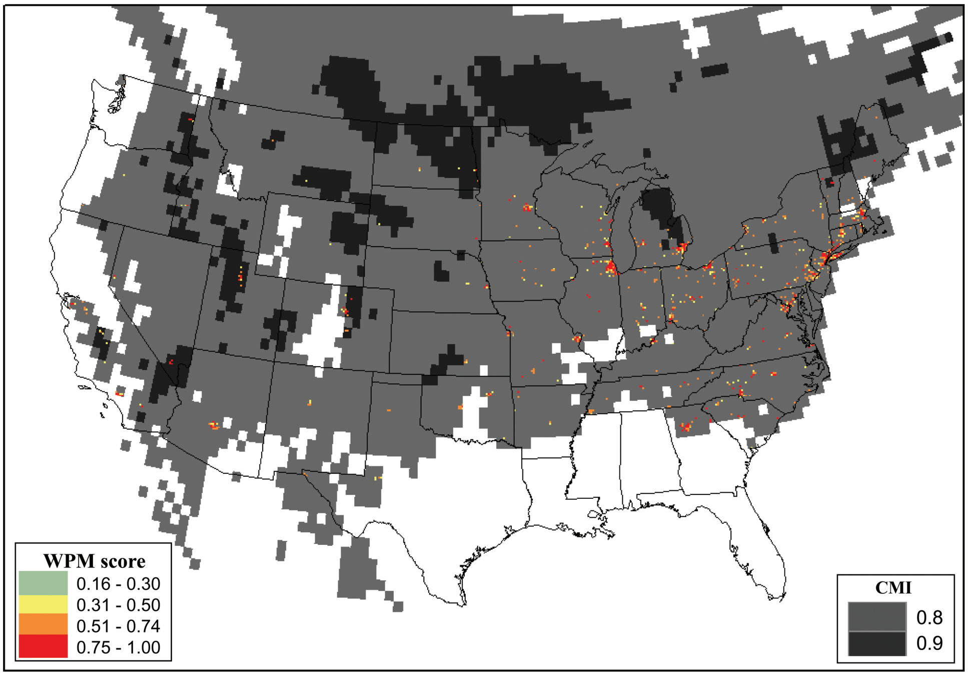

Fig. 9. Optimal map illustrating potential establishment area of *Trichoferus campestris* by combining likelihood entry at final destinations of WPM and wood products, with climate conducive for the beetle's development and survival.

risk in the associated WPM (Eyre et al. 2018, S. Krishnankutty, unpublished data). In addition, stone products are often stored outdoors, as they are generally not affected by weather conditions, and therefore provide opportunity for adult wood borers to escape from pallets into the environment. Other commodities associated with the WPM pathway are likely stored indoors, which may somewhat reduce, but not eliminate, the risk of escape into the environment. Few wood products were found harboring *T. campestris*, but this may reflect, in part, low inspection rates at warehouses and low awareness or incentive by companies to report live insects they may encounter in wooden products. Overall, however, the trend towards positive correlation between risk of introduction and size of human populations is consistent with findings of other studies demonstrating the vulnerability of both urban areas and agricultural and forest lands at the urban interface to introductions of invasive pests (Colunga-Garcia et al. 2010, Colunga-Garcia and Haack 2015). Inland detections appear to suggest the use of final-destination approach to predicting high-risk introduction points, although these detections are biased due to nonrandom selection of trap-survey areas. Most detections occurred in and around urban centers deemed risky for *T. campestris* introduction. The three counties with established populations in Illinois, Utah and Wisconsin contain high-risk urban centers. Concordance between at-risk centers and detection is highlighted in Utah and Colorado, where the species was detected in or near the high-risk centers mapped within the two states (Fig. 6). Areas without detections across several southwestern and northern states may be due to lack of survey efforts, or failure to detect beetle presence, or both.

Intended destinations of intercepted WPM appear to have some predictive value as proxies for realized destinations of infested WPM. The underlying assumption for this is that goods received by the importing businesses are often shipped repeatedly from established trade partners or export centers who construct wood packaging from locally sourced wood, while only a fraction of the WPM from the area can be inspected at U.S. ports. Before the pheromone of *T. campestris* was identified (Ray et al. 2019), the beetle was discovered in three IDCs. The two Illinois counties were surveyed by CAPS (using traps baited with nonspecific lures), while the Utah survey was initiated after the discovery of multiple beetles in fruit orchards and golf courses (Ray et al. 2019); these IDCs now have established populations (CERIS 2019). Additionally, detections in counties neighboring IDCs also support the notion of IDCs as proxies. In total, 40% of 27 counties intended for delivery of intercepted WPM were discovered to have had detections or presumed populations of the beetle in the same or neighboring counties.

Climate suitability, based on the CMI, incorporating temperature and precipitation via the CLIMEX Match Climate model, suggests potential for *T. campestris* to establish throughout northern and central states of the contiguous United States (Fig. 5). Poor climatic suitability is predicted in the southern and western U.S. states, and at higher elevations, although in some areas (e.g., the interior U.S. highlands of Arkansas, Missouri, and Oklahoma) suitability is apparently reduced at elevations as low as 500 m above sea level. Some precision in the model was lost due to the limited number of factors used to generate the CMI (temperature and precipitation), but the CMI was likely hindered more substantially by lack of precise information on the native distribution of the species in China. Distribution there was reported only on a province-wide level and necessitated a very crude estimation of location in the center of each province. Lack of biological data on developmental temperature thresholds also limited our ability to predict where *T. campestris* might establish. We determined that winter chilling increases survival of the larva to the adult stage in a laboratory (H. Nadel, unpublished data), but no information is available on the low temperature threshold or duration required to complete development. A low temperature period appears to be required for *T. campestris* larvae to induce pupation. Laboratory trials showed that larvae reared to maturity on artificial diet at 23°C rarely pupated unless exposed to 10°C for 3 mo (H. Nadel, unpublished data). We note, however, that highly suitable areas scoring 0.9 on the CMI map coincide with winter temperatures reaching lows of ≤10°C for at least 90 d from November to February every year, based on weather data from the last 20 yr (1998–2018). Areas with basal scores of 0.7 and below either fail to sustain cool winter temperatures for the needed duration and/or deviate from precipitation patterns that influence the presence of the beetle's host plants or other biotic or abiotic factors in its environment.

Six of 15 (40%) U.S. ports that reported interceptions of *T. campestris* and 17 of 27 (63%) IDCs of cargo infested with the insect (Supp Table S3 [online only], Table 1) are predicted to be located in climatically suitable regions (Fig. 5), raising the possibility that the larvae could survive to the adult stage if the wood remains there. In conjunction with appropriate wood disposal, deploying sufficient detection resources at receiving ports and at cargo destination counties with high CMI may enable early detection and early response to reduce the chance of *T. campestris* establishment. Climate matching also indicated that several high-likelihood sites for *T. campestris* entry (Fig. 6) exist in the southern part of the United States. Although outside the population establishment zone, infested WPM may ultimately be distributed from those localities to climatically suitable areas further north where the beetle's potential for establishment is high.

The discovery of populations of *T. campestris* in Illinois, Utah, and Wisconsin, along with widespread destinations of potentially infested WPM in climatically suitable areas, suggests a risk of extant or future establishment in other states. Thus, determining if additional established populations exist in other parts of the United States is important for efforts aiming to understand the host range, damage, and economic impacts of this insect. However, surveying all remaining states for this insect is not economically feasible, and poor knowledge of the biology of this pest hinders efforts to quickly and precisely characterize establishment risk in other states. Therefore, an approach that combined mapped risk of *T. campestris* entry at final destinations of WPM and wood products, combined with climate conducive for the beetle's development and survival (Fig. 9) was adopted to provide a means to identify potential areas of establishment by *T. campestris*. This map tool, along with the recently discovered *T. campestris*-specific pheromone (Ray et al. 2019), can be valuable towards early detection surveys for this insect. A better insight on the risk of establishment of this insect in the United States can be achieved with addition of data on biology and host suitability. Further modeling studies could be done to predict habitat suitability using tools such as VisTrails SAHM (Morisette et al. 2013); these studies could use inland detections as the binary response and CMI and WPM scores as the predictors to provide additional insights into suitable habitats outside those encompassing inland detections. The results presented here, along with the best available scientific information, may enhance pest survey efforts leading to early detection.

Supplementary Data

Supplementary data are available at *Annals of the Entomological Society of America* online.

Acknowledgments

We gratefully acknowledge the efforts of CBP agriculture specialists and APHIS identifiers at participating ports to collect, package, and send insects and wood samples to the Otis Laboratory. We thank Pete Reagel (USDA APHIS) for conducting the early phase of research in 2012 – 2014. Sian Bailey, Hannah Cornwell, Lara Trozzo, Nevada Trepanowski, Kendra Vieira and Marjorie Palmeri are gratefully acknowledged for their technical assistance at Otis Lab. We thank Joe Francese (USDA APHIS) and Kristopher Watson (Utah Department of Agriculture and Food) for providing trapping data for *Trichoferus campestris* in the United States. We also thank Ricardo Valdez and Valerie Defeo (USDA APHIS) for providing access to the ARM database. Special thanks are due to the staff at the USDA APHIS National Identification Service and the USDA Agricultural Research Service Systematic Entomology Laboratory for specimen processing. The manuscript was improved with the help of two anonymous reviewers. Mention of a product or company is for informational purposes and does not constitute its endorsement by the USDA. The findings and conclusions in this preliminary publication have not been formally disseminated by the U.S. Department of Agriculture and should not be construed to represent any agency determination or policy. This work was funded by the Intramural Research Program of the U.S. Department of Agriculture, Animal and Plant Health Inspection Service, through Agricultural Quarantine Inspection fees.

References Cited

Allen, E. A., and L. M. Humble. 2002. Nonindigenous species introductions: a threat to Canada's forests and forest economy. Can. J. Plant Pathol. 24: 103–110.

Brockerhoff, E. G., A. M. Liebhold, and H. Jactel. 2006. The ecology of forest insect invasions and advances in their management. Can. J. For. Res. 36: 263–268.

Bullas-Appleton, E., T. Kimoto, and J. J. Turgeon. 2013. Discovery of *Trichoferus campestris* (Coleoptera: Cerambycidae) in Ontario, Canada and first host record in North America. Can. Entomol. 146: 111–116.

Cavey, J. F. 1998. Solid Wood Packing Material from China, initial pest risk assessment on certain wood boring beetles known to be associated with cargo shipments: Asian Longhorned Beetle *(Anoplophora glabripennis)*, *Ceresium*, *Monochamus*, and *Hesperophanes*. United States Department of Agriculture, Animal and Plant Health Inspection Service, Riverdale, MD.

(CERIS) Center for Environmental and Research Information Systems. 2019. Purdue University. Survey Status of Velvet longhorned beetle - *Trichoferus campestris*. http://pest.ceris.purdue.edu/map.php?code=INALQPA&year=2018

Cocquempot, C. 2006. Alien longhorned beetles (Coleoptera Cerambycidae): original interceptions and introductions in Europe, mainly in France, and notes about recently imported species. Redia. 89: 35–50.

Colunga-Garcia, M., and R. A. Haack. 2015. Following the transportation trail to anticipate human-mediated invasions in terrestrial ecosystems, pp. 35–48. In R. C. Venette (ed.), Pest risk modelling and mapping for invasive alien species. CAB International, Boston, MA.

Colunga-Garcia, M., R. A. Magarey, R. A. Haack, S. H. Gage, and J. Qi. 2010. Enhancing early detection of exotic pests in agricultural and forest ecosystems using an urban-gradient framework. Ecol. Appl. 20: 303–310.

Dascălu, M.-M., R. Serafim, and Å. Lindelöw. 2013. Range expansion of *Trichoferus campestris* (Faldermann) (Coleoptera: Cerambycidae) in Europe with the confirmation of its presence in Romania. Entomol. Fenn. 24: 142–146.

European and Mediterranean Plant Protection Organization (EPPO). 2009. *Hesperophanes campestris*. EPPO Bull. 39: 51–54.

Eyre, D., and R. A. Haack. 2017. Invasive cerambycid pests and biosecurity measures, pp. 563–618. In Q. Wang (ed.), Cerambycidae of the world: biology and pest management. CRC Press, Boca Raton, FL.

Eyre, D., R. Macarthur, R. A. Haack, Y. Lu, and H. Krehan. 2018. Variation in inspection efficacy by member states of wood packaging material entering the European Union. J. Econ. Entomol. 111: 707–715.

Grebennikov, V. V., B. D. Gill, and R. Vigneault. 2010. *Trichoferus campestris* (Faldermann) (Coleoptera: Cerambycidae), an Asian wood-boring beetle recorded in North America. Coleopt. Bull. 64: 13–20.

Haack, R. A. 2006. Exotic bark- and wood-boring Coleoptera in the United States: recent establishments and interceptions. Can. J. For. Res. 36: 269–288.

Haack, R. A., K. O. Britton, E. G. Brockerhoff, J. F. Cavey, L. J. Garrett, M. Kimberley, F. Lowenstein, A. Nuding, L. J. Olson, J. Turner, et al. 2014. Effectiveness of the International Phytosanitary Standard ISPM No. 15 on reducing wood borer infestation rates in wood packaging material entering the United States. Plos One. 9: e96611.

Hastings, J. M., K. M. Potter, F. H. Koch, M. Megalos, and R. M. Jetton. 2017. Prioritizing conservation seed banking locations for imperiled hemlock species using multi-attribute frontier mapping. New For. 48: 301–316.

International Plant Protection Convention (IPPC). 2018. International standards for phytosanitary measures: ISPM 15, regulation of wood packaging material in international trade. IPPC, Food and Agriculture Organization of the United Nations, Rome, Italy.

Iwata, R., and F. Yamada. 1990. Notes on the biology of *Hesperophanes campestris* (Faldermann) (Col., Cerambycidae), a drywood borer in Japan. Material und Organismen 25: 305–313.

Kriticos, D. J. 2012. Regional climate-matching to estimate current and future sources of biosecurity threats. Biol. Invasions 14: 1533–1544.

Liebhold, A. M., W. L. MacDonald, D. Bergdahl, and V. C. Mastro. 1995. Invasion by exotic forest pests: a threat to forest ecosystems. For. Sci. Monogr. 30: 1–49.

Maier, C. T. 2017. Cerambycidae (Coleoptera) accidentally introduced into Connecticut from China or from other areas in the United States. Proc. Entomol. Soc. Wash. 119: 423–429.

de Morais, E. G. F., M. C. Picanço, K. L. B. Lopes-Mattos, R. S. Bourchier, R. M. S. Alves Meira, and R. W. Barreto. 2013. *Diclidophlebia smithi* (Hemiptera: Psyllidae), a potential biocontrol agent for *Miconia calvescens* in the Pacific: population dynamics, climate-match, host-specificity, host-damage and natural enemies. Biol. Control 66: 33–40.

Morisette, J. T., C. S. Jarnevich, T. R. Holocombe, C. B. Talbert, D. Ignizio, M. K. Talbert, C. Silva, D. Koop, A. Swanson, and N. E. Young. 2013. VisTrails SAHM: visualization and workflow management for species habitat modelling. Ecography. 36: 129–135.

Moser, W. K., E. L. Barnard, R. F. Billings, S. J. Crocker, M. E. Dix, A. N. Gray, G. G. Ice, M.-S. Kim, R. Reid, S. U. Rodman, et al. 2009. Impacts of monnative invasive species on US forests and recommendations for policy and management. J. For. 107: 320–327.

National Invasive Species Council (NISC). 2003. General guidelines for the establishment and evaluation of invasive species early detection and rapid response systems. Version 1. NISC, Washington, DC.

Pennacchio, F., L. Marianelli, F. Binazzi, V. Francardi, F. Paoli, R. Griffo, and P. F. Roversi. 2016. First interception of *Trichoferus campestris* (Faldermann, 1835) (Coleoptera Cerambycidae Cerambycinae) in Italy. Redia 99: 59–62.

Phillips, C. B., J. M. Kean, C. J. Vink, and J. A. Berry. 2018. Utility of the CLIMEX 'match climates regional' algorithm for pest risk analysis: an evaluation with non-native ants in New Zealand. Biol. Invasions. 20: 777–791.

Ray, A. M., J. A. Francese, Y. Zou, K. Watson, D. J. Crook, and J. G. Millar. 2019. Isolation and identification of a male-produced aggregation-sex pheromone for the velvet longhorned beetle, *Trichoferus campestris*. Sci. Rep. 9: 4459.

Robertson, M. P., D. J. Kriticos, and C. Zachariades. 2008. Climate matching techniques to narrow the search for biological control agents. Biol. Control 46: 442–452.

Sutherst, R. W., G. Maywald, and D. J. Kriticos. 2007. Climex Version 3. Hearne Scientific Software Pty. Ltd., Melbourne, Australia.

Venette, R. C. 2017. Climate analyses to assess risks from invasive forest insects: simple matching to advanced models. Curr. Forestry. Rep. 3: 255–268.

Wallenmaier, T. 1982. A pest risk assessment of wood-boring insects associated with wood products moving in international commerce. United States Department of Agriculture, Animal and Plant Health Inspection Service, Riverdale, MD

Wu, Y., N. F. Trepanowski, J. J. Molongoski, P. F. Reagel, S. W. Lingafelter, H. Nadel, S. W. Myers, and A. M. Ray. 2017. Identification of wood-boring beetles (Cerambycidae and Buprestidae) intercepted in trade-associated solid wood packaging material using DNA barcoding and morphology. Sci. Rep. 7: 40316.

Xinming, Y., and G. Miao. 1999. Study on the reproductive behavior of *Trichoferus campestris* (Faldermann) (Coleoptera: Cerambycidae), pp. 158–159. *In* Jin, Z., Liang Q., Liang, Y., Tan, X., & Guan, L. (eds.), Proceedings, 7th International Working Conference on Stored-product Protection, 14–19 October 1998, Beijing, China. Sichuan Publishing House of Science and Technology, Chengdu, China.

Yemshanov, D., F. H. Koch, Y. Ben-Haim, M. Downing, F. Sapio, and M. Siltanen. 2013. A new multicriteria risk mapping approach based on a multiattribute frontier concept. Risk Anal. 33: 1694–1709.

Yemshanov, D., F. H. Koch, B. Lu, B. D. Lyons, J. P. Prestemon, T. Scarr, and K. Koehler. 2014. There is no silver bullet: the value of diversification in planning invasive species surveillance. Ecol. Econ. 104: 61–72.

Yemshanov, D., F. H. Koch, M. Ducey, and R. A. Haack. 2015. Towards reliable mapping of biosecurity risk: incorporating uncertainty and decision makers' risk aversion, pp. 217–237. *In* F. Jarrad, S. Low-Choy and K. Mengersen (eds.), Biosecurity surveillance: quantitative approaches. CAB International, Wallingford, UK.