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The Establishment Risk of *Lycorma delicatula* (Hemiptera: Fulgoridae) in the United States and Globally

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Subject Editor: Charles Burks

Received 5 June 2019; Editorial decision 22 August 2019

Abstract

Native to Asia, the spotted lanternfly, *Lycorma delicatula* (White), is an emerging pest of many commercially important plants in Korea, Japan, and the United States. Determining its potential distribution is important for proactive measures to protect commercially important commodities. The objective of this study was to assess the establishment risk of *L. delicatula* globally and in the United States using the ecological niche model MAXENT, with a focus on Washington State (WA), where large fruit industries exist. The MAXENT model predicted highly suitable areas for *L. delicatula* in Asia, Oceania, South America, North America, Africa, and Europe, but also predicted that tropical habitats are not suitable for its establishment, contrary to published information. Within the United States, the MAXENT model predicted that *L. delicatula* can establish in most of New England and the mid-Atlantic states, the central United States and the Pacific Coast states, including WA. If introduced, *L. delicatula* is likely to establish in fruit-growing regions of the Pacific Northwest. The most important environmental variables for predicting the potential distribution of *L. delicatula* were mean temperature of driest quarter, elevation, degree-days with a lower developmental threshold value of 11°C, isothermality, and precipitation of coldest quarter. Results of this study can be used by regulatory agencies to guide *L. delicatula* surveys and prioritize management interventions for this pest.

Key words: spotted lanternfly, ecological niche model, MAXENT, tree of heaven

The spotted lanternfly, *Lycorma delicatula* (White), is pest of numerous commercially important plants in China (Liu 1939) and has been reported from Vietnam (Hua 2000, Han et al. 2008), but has recently (2006) become common in central and southern Korea, apparently introduced from China (Han et al. 2008, Kim et al. 2011). *Lycorma delicatula* has also invaded Japan (Kim et al. 2013) and more recently the United States, specifically in Berks County in Pennsylvania (Barringer et al. 2015, Dara et al. 2015). Populations of *L. delicatula* were also detected in 2018 and 2019 in New Jersey, northern Virginia, and northern Delaware (Anonymous 2019). Damage caused by *L. delicatula* is through its feeding on phloem in leaves and stems, which weakens plants and causes sap to exude, resulting in mold growth. Mold growth is augmented by the honeydew that *L. delicatula* deposits on leaves, fruits, and stems of host plants. *Lycorma delicatula* reportedly attacks more than 70 plant species (Dara et al. 2015), with its major host being the tree of heaven, *Ailanthus altissima* (Mill.) Swingle (Simaroubaceae) (Barringer et al. 2015, Dara et al. 2015), a plant native to northeast and central China (Miller 1990), Taiwan (USDA-ARS [United States Department of Agriculture-Agricultural Research Service], 2011), and northern

Vietnam (Kowarik and Säumel 2007). Other important hosts of *L. delicatula* include Chinaberry tree (*Melia azedarach* L.) (Meliaceae), Chinese mahogany (*Toona sinensis* M. Roem) (Meliaceae), black walnut (*Juglans nigra* L.) (Juglandaceae), hops (*Humulus lupulus* L.) (Cannabaceae), and *Vitis* (Vitaceae), and *Prunus* (Rosaceae) species (USDA-APHIS 2017).

The USDA has identified *L. delicatula* as a potential pest of grapes, apples, cherries, apricots, peaches, and several other fruit and timber tree species (USDA-APHIS 2018, 2019). The Canadian Food Inspection Agency has recognized it as a potential threat to grape, tree fruit, and forest industries in Canada (CFIA 2018). Thus, *L. delicatula* is an important pest with far-reaching negative economic impacts for fruit and forest industries, prompting studies to investigate its biology, physiology, and ecology in North America (USDA-APHIS 2017).

Lycorma delicatula is a univoltine, phytophagous planthopper that overwinters in the egg stage (Dara 2015). Eggs are laid in masses that are then covered by the ovipositing female with a foamy coating. Egg masses may be laid on tree trunks or branches, nearby rocks, or inanimate objects such as walls and fenceposts. Adults are active

from July to December, with eggs laid from September to December. For detailed information on the biology of *L. delicatula*, the reader is referred to Park (2009), Dara et al. (2015), and USDA-APHIS (2017, 2018). Degree-day phenology models have yet to be developed for this species, but lower temperature threshold levels of 8°C and 11°C were suggested by different authors (EPPO 2016, Jung et al. 2017, Moylett and Molet 2018).

There is limited information on the potential distribution of *L. delicatula* globally and in the United States. Potential distribution maps indicate relative habitat suitability for an area and species of interest. Such maps can be used by regulatory agencies to guide surveys and prioritize pest management interventions. Using the process-based ecological niche model (ENM) CLIMEX (Jung et al. 2017), it was found that *L. delicatula* has high potential distribution in the United States, Brazil, Mexico, Congo, China, Japan, and the southern part of Korea, as well as the United Kingdom, France, Belgium, Switzerland, Spain, and Italy in Europe. Furthermore, about 60% of Korea is suitable for *L. delicatula* establishment (Jung et al. 2017).

Another ENM approach for predicting species' distributions is MAXENT (Phillips et al. 2006, Elith et al. 2010). This approach characterizes the species' known optimal environmental locations through geographically referenced species occurrence data and then links these data with the corresponding environmental data (from the same or different locations) to identify similar sites with optimal environmental conditions (Phillips et al. 2006, Phillips and Dudík 2008, Elith et al. 2010). To our knowledge, there is no published global potential distribution map of *L. delicatula* developed using MAXENT. Comparison of results using MAXENT with those using CLIMEX (Jung et al. 2017) would be useful for interpreting the utility of these methods, especially where inconsistencies arise.

One region within the United States that could be seriously impacted by invasion of *L. delicatula* is the Pacific Northwest, in particular Washington State (WA), where there is a sizable and thriving fruit industry. The dollar value of apples (*Malus domestica* Borkhausen) (Rosaceae) in WA in 2017 was approximately US\$2.4 billion (NASS 2018a); and for sweet cherries (*Prunus avium* [L.] L.) (Rosaceae), approximately US\$1.0 billion (Northwest Horticultural Council 2018). In addition, the wine grape (*Vitis vinifera* L.) (Vitaceae) industry in WA has a total economic impact of around US\$4.8 billion (Washington State Wine Commission 2019), while the hop industry there was valued at US\$427 million (NASS 2018b). Clearly, it would be useful for fruit and hop growers, regulatory agencies, and risk analysts to identify areas in the United States and WA where *L. delicatula* can potentially establish.

The objective of this study was to assess the establishment risk of *L. delicatula* globally and in the United States using MAXENT, with a focus on WA. First, we developed a global potential distribution map of *L. delicatula* by combining species presence data obtained from the insect's native and invasive ranges. Second, we selected biologically relevant environmental variables for modeling the insect's potential distribution. Third, we applied MAXENT to generate predictive maps of *L. delicatula* potential distribution.

Materials and Methods

Lycorma delicatula Presence Data

A total of 240 presence records obtained from different sources were used for developing the MAXENT model. These included published articles (Han et al. 2008, Kim et al. 2013, Park et al. 2013, Barringer et al. 2015, Jung et al. 2017); the Global Biodiversity Information Facility database (GBIF 2018); and research collaborators in New

Jersey, United States, and China. Before MAXENT modeling, we checked the presence data for reliability. Generally, published data with projection information and complete metadata are reliable (here we used only reliable data). Conversely, data with missing projection information and incomplete metadata are unreliable. Occurrence points that fall on unexpected areas such as water bodies are likely caused by human errors and were not included in our analysis. The data were then converted to similar projections and subjected to spatial filtering in ArcGIS software and SDMtoolbox (Brown 2014, ESRI 2016, Brown et al. 2017). These steps allowed us to remove duplicate records, reduce spatial autocorrelation, and ensure only high-quality data were used in the MAXENT modeling.

Environmental Data

The environmental datasets considered for modeling *L. delicatula* included the 19 current bioclimatic variables representing average values for the years 1970–2000 and obtained from WorldClim website (Hijmans et al. 2005, WorldClim 2016), global elevation dataset obtained from the USGS website (SRTM 2010), and degree-day variables calculated in ArcGIS using 8°C and 11°C lower temperature threshold values. Monthly temperature values from the WorldClim dataset were used to calculate degree-day variables. Environmental variables were checked for cross-correlations using SDMtoolbox and less correlated variables (Pearson's correlation values, $r \leq \pm 0.8$) were included in the analysis. We prepared all environmental datasets at two spatial extents. The first dataset (training dataset) had a relatively small spatial extent and was used to calibrate/parameterize the MAXENT model, while the second data set (prediction dataset) was prepared at a global scale and was used for projecting the MAXENT model. We created the training dataset in ArcGIS by specifying a 300-km distance from the *L. delicatula* presence records (minimum convex polygon method) (Brown 2014; Fig. 1.). All datasets were prepared at the spatial resolution of the bioclimatic variables (~900 m).

MAXENT Modeling

The MAXENT ENM technique, which gives reasonable predictions when compared with other ENMs (Elith et al. 2010; Kumar et al. 2015, 2016), was selected for predicting the potential distribution of *L. delicatula* in this study. MAXENT is a species-presence only method developed for mapping species distributions (Phillips et al. 2006, Phillips and Dudík 2008, Elith et al. 2011). Based on Phillips et al. (2006), the technique relies on the *Maximum Entropy* principle, which takes into consideration the information generated by species-presence data while making minimal assumptions about the unknown information (areas where predictions will be made). Here, we used MAXENT version 3.4.1, specifying a 10-fold cross-validation approach with the linear, quadratic, product, and hinge features selected. Additionally, we selected a *regularization multiplier* value of one (default value) and the *Multivariate Environmental Similarity Surfaces (MESS) analysis* options. We selected these final settings after running several models and examining response curves for realistic representation (over-fitted response curves are unrealistic) and evaluating the area under the receiver characteristic curve (AUC) values for model accuracy (models with AUC values close to one are considered more reasonable than models with AUC values close to 0.5, which are considered random).

We evaluated final MAXENT predictions using an independent dataset and three evaluation metrics, AUC, sensitivity, and Kappa statistic (Cohen 1960, Hanley and McNeil 1982, Fielding and Bell 1997). The independent dataset included 86 points with an equal

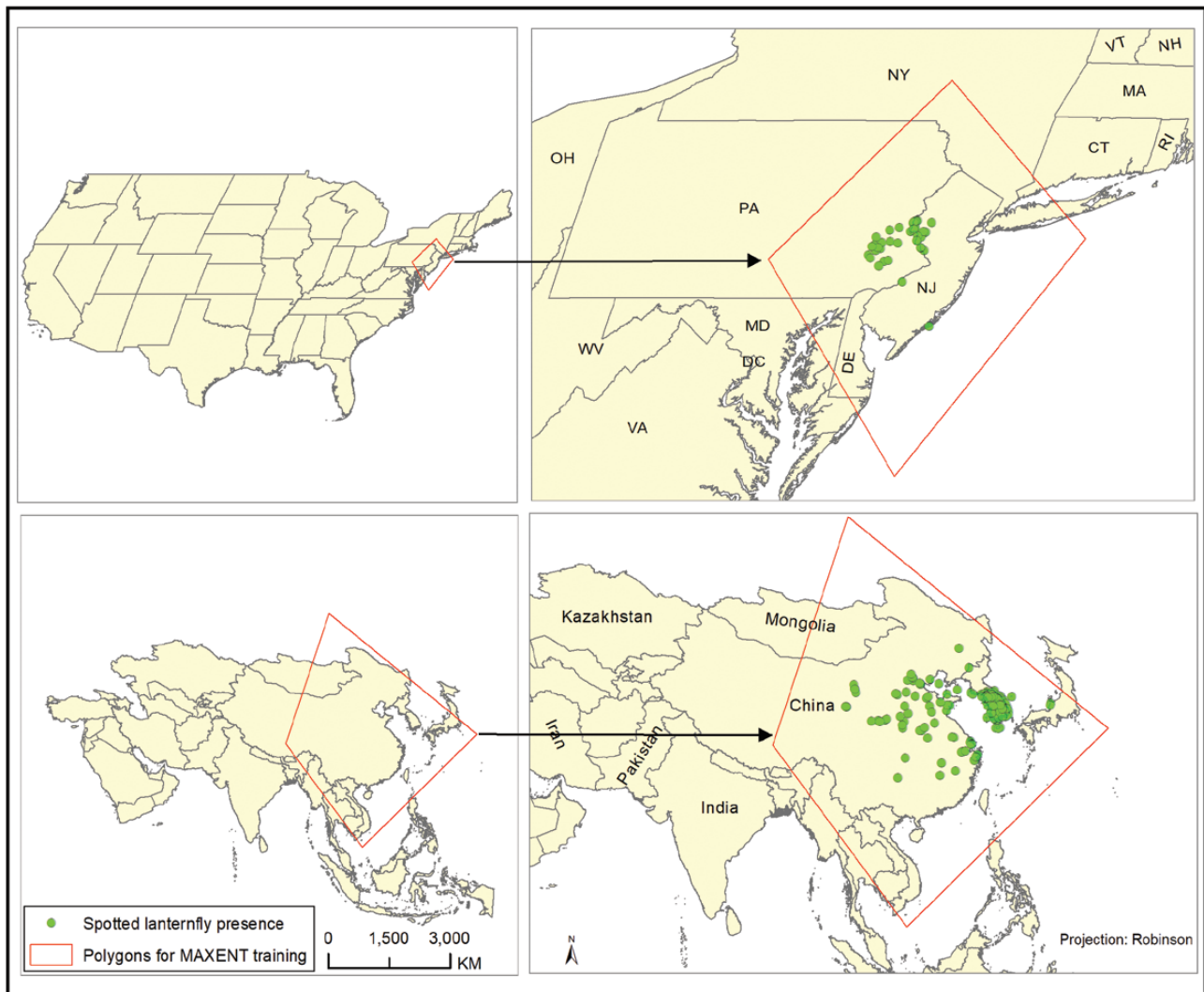


Fig. 1. *Lycorma delicatula* presence locations. Green circles show *L. delicatula* presence locations and red polygons mark the boundaries within which the MAXENT model was calibrated. Color figures are available in the online version only.

number of presence and absence points. The test data were obtained both from the species' native and invasive ranges. As in the case of AUC, when predicting potential distribution of invasive species, higher sensitivity values (one or close to one) are desired. The Kappa statistic is interpreted as having poor, moderate, substantial, and perfect agreement among the test data and prediction data when its values are ≤ 0 , 0.41–0.60, 0.61–0.80, and 0.81–1, respectively (Cohen 1960, McHugh 2012). Model uncertainty was assessed via MESS analysis, which identifies locations in the projection dataset with dissimilar environmental values from the training dataset, also referred as novel areas (Elith et al. 2010).

Results

The MAXENT model predicted highly suitable areas for *L. delicatula* in Asia (Korea, Japan, China), Oceania (Australia, New Zealand), South America (Argentina, Chile, Uruguay), North America (US, Mexico), Africa (South Africa, Namibia, Morocco), and Europe (including Spain, France, Italy, Germany, Poland, Russia, Ukraine, Romania, Hungary, Turkey and eastern Kazakhstan) (Fig. 2). Based

on the MAXENT model, tropical habitats are not suitable for *L. delicatula* establishment.

Within the United States, MAXENT predicted that *L. delicatula* can establish in Pennsylvania, New Jersey, Virginia, West Virginia, Delaware, New York, Massachusetts, Rhode Island, New Hampshire, Connecticut, Maine, Maryland, North Carolina, Kentucky, Ohio, Michigan, Indiana, Illinois, Iowa, Missouri, Kansas, Nebraska, California, WA, and Oregon (Fig. 3). If introduced, *L. delicatula* is likely to establish in the Pacific Northwest. Many counties in WA have suitable habitats for *L. delicatula* establishment; the top-four counties with highly suitable habitats are Benton, Franklin, Yakima, and Walla Walla (Fig. 4).

The most important environmental variables for predicting the potential distribution of *L. delicatula* were mean temperature of driest quarter (Bio 9), elevation, degree-day with lower developmental threshold value of 11°C, isothermality (Bio 3), and precipitation of coldest quarter (Bio 19) (Fig. 5, Table 1). *Lycorma delicatula* appears to do well where the mean temperature of the driest quarter is between -7°C and 7°C (Fig. 5a), the elevation is near zero m (Fig. 5b), the degree-days are above 1,000 d

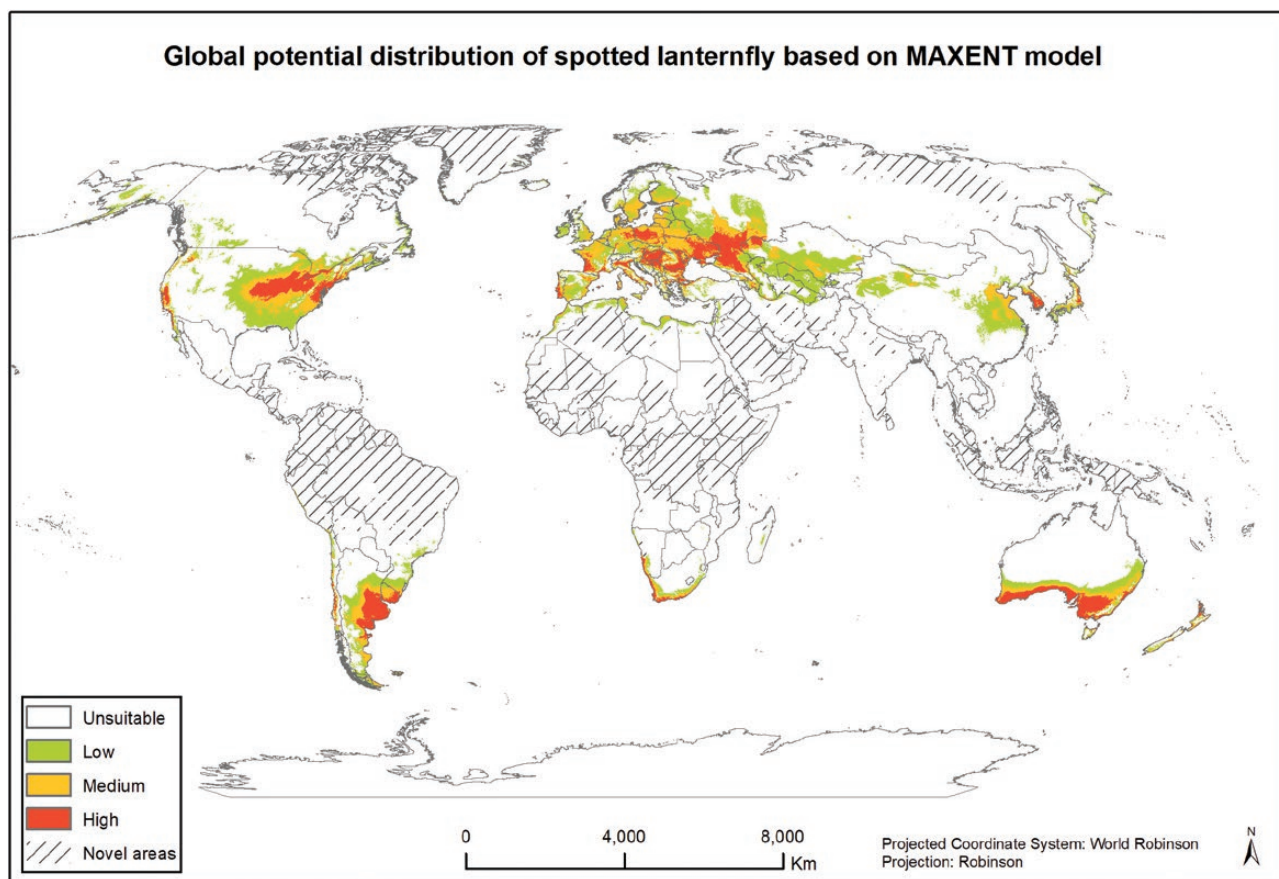


Fig. 2. Global potential distribution of *L. delicatula*. Areas shaded in red, yellow, and green show high, medium, and low suitability, respectively. Blank areas indicate unsuitable habitats and hash marks indicate environmentally dissimilar areas among the training and projection datasets (novel areas). The map was produced by classifying MAXENT logistic outputs values into four classes. Color figures are available in the online version only.

(Fig. 5c), and the isothermality is between ~ 25 and $\sim 35^\circ\text{C}$ (Fig. 5d). Evaluation tests performed using independent data showed that the final MAXENT model had AUC, sensitivity, and Kappa values of 0.89, 0.8, and 0.67, respectively, indicating relatively high prediction accuracy.

Discussion

Results using MAXENT indicate that *L. delicatula* has an expansive potential distribution across the northern and southern hemispheres, but that it cannot occupy tropical zones, indicating it is adapted to lower temperature climates. If introduced, *L. delicatula* can be established in the top five grape growing European countries including Spain, France, Italy, Portugal, and Romania (OIV 2017), suggesting that the potential economic impact of *L. delicatula* in Europe is substantial. Similarly, *L. delicatula* can establish in western U.S. states where suitable host plants such as apple and grape are widely grown. The 2018 total production values of apples, hops, cherries, grapes, and pears in WA, Oregon, and California was \sim US\$10.5 billion (NASS 2018c; Table 2). Recent reports indicate that hop acreages are steadily increasing in the northwestern United States (NASS 2018b, 2019). Thus, the potential negative economic impact of *L. delicatula* on agriculture in western United States is also substantial. Therefore, *L. delicatula* preventive measures should be implemented, and vigilant steps for early detection such as surveying and trapping should be considered. Potentially suitable habitats for *L. delicatula* exist in

a number of temperate tree fruit-growing states within the United States, including regions in WA, Oregon, California, Michigan, and New York. In addition to the large tree fruit industries there, the grape industry is also sizable in WA and California, while the hop industry is sizable in WA and Oregon (Table 2). Thus, the overall economic impact of the pest on agriculture if it were to invade those states potentially could be far-reaching.

The potential of *L. delicatula* establishing quickly in the United States outside of Pennsylvania and New Jersey may depend in part on the presence of tree of heaven in other regions. Tree of heaven, unlike many members of its genus, is a temperate plant not found in the tropics. It was introduced in the 1700s and 1800s into North America, where it has been a pest for many years (Hoshovsky 1988). Importantly for the potential distribution of *L. delicatula*, tree of heaven is found throughout the United States, essentially in every state where our model predicts *L. delicatula* can establish, including in the Pacific Northwest and California (Hu 1979, Hoshovsky 1988, Miller 1990, Todd 2014, USDA 2019). Thus, assuming there are sufficient densities of this tree across the United States, host plant availability may not be a limitation for the pest to spread widely. *Ailanthus* is most abundant in urban environments (Huebner 2003, Wenning 2014), so human spread of the insect should be a concern as well. Tree of heaven is listed as an invasive or noxious weed in Connecticut, Massachusetts, New Hampshire, and Vermont (Todd 2014), implying its high prevalence in those states, and thus their potential for *L. delicatula* establishment.

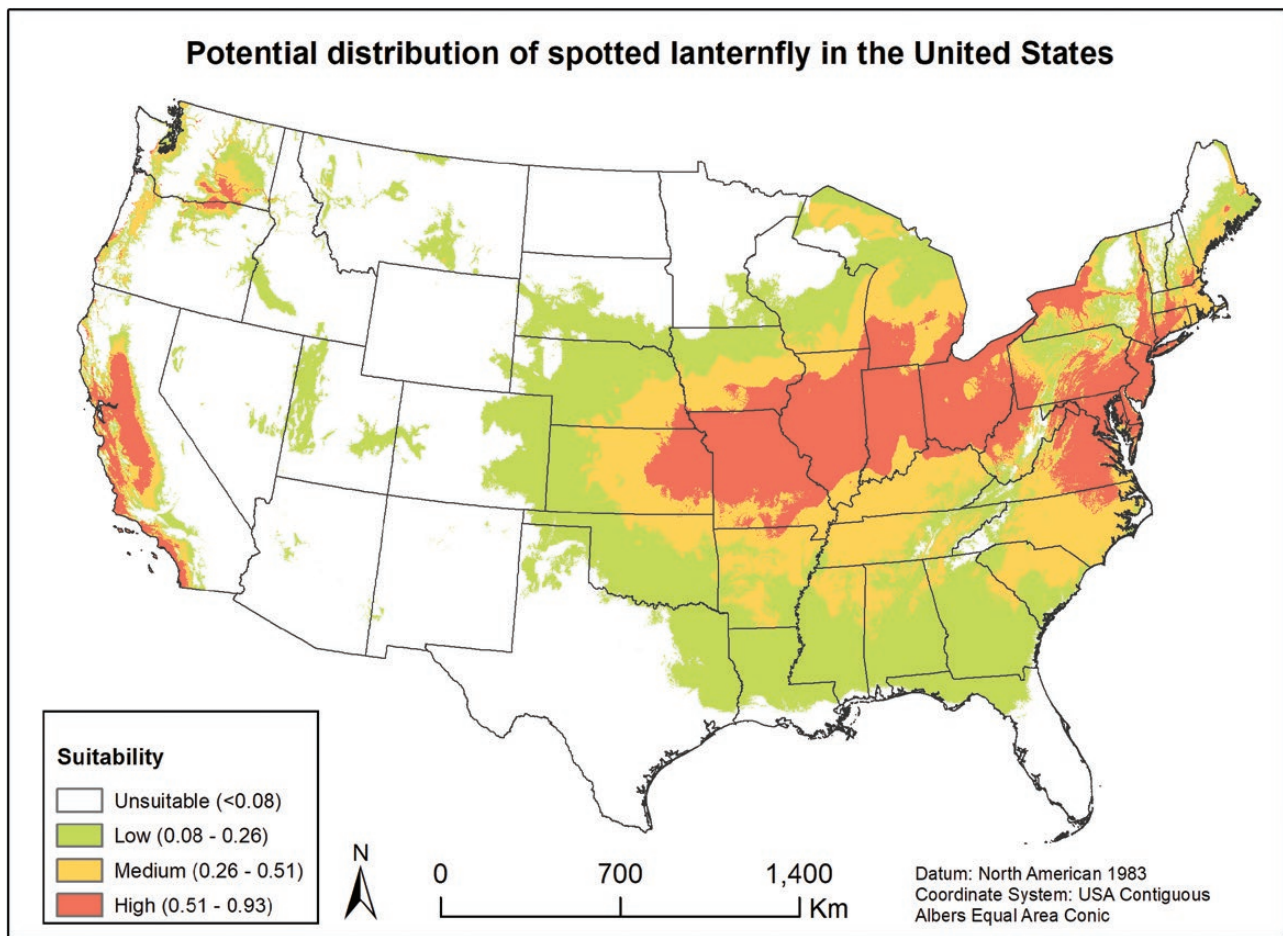


Fig. 3. Potential distribution of *L. delicatula* in the United States. Areas shaded in red, yellow, and green indicate high, medium, and low suitability, respectively. Unshaded/blank areas indicate areas that are unsuitable for *L. delicatula* establishment. Color figures area available in the online version only.

In WA, tree of heaven is considered a noxious weed (Washington State Noxious Weed Control Board 2011). The earliest record of tree of heaven in WA is 1929 in Whitman County (Washington State Noxious Weed Control Board 2011). By 2018, 15 WA counties had become infested with tree of heaven, including >1,000 acres in Chelan, Douglas, and Klickitat Counties (the most heavily infested counties) and 10–100 acres in Yakima County (Haubrich 2018). It is also considered a noxious plant in Oregon (Anonymous 2014, Breen 2019), where it was first recorded in 1904 in Wasco County and is very abundant along the Columbia River (Oregon Department of Agriculture 2019), where the habitat is also very suitable for *L. delicatula* (lower edge of WA) (Fig. 4). In WA, trees are found in roadsides, bluffs, wet meadows, riverbanks, and urban areas (Washington State Noxious Weed Control Board 2011). Thus, aside from suitable climate as predicted by our model, the Pacific Northwest and WA has the insect's major host spread across a large region.

There were several major differences in MAXENT predictions for *L. delicatula* here and those using CLIMEX (Jung et al. 2017). First, CLIMEX predicted low suitability of European countries and the northeastern United States. In contrast, our model predicted suitable habitats in at least 11 European countries and large portions of the Northeast and Pacific Northwest regions of the United States. The detection of *L. delicatula* in northeastern United States (e.g., New York, Delaware) (Anonymous 2019) confirms that these areas

are suitable for its establishment. Second, CLIMEX predicted high suitability for tropical countries and the southeastern United States (warmer regions), while our model indicated tropical habitats and warmer climates are unsuitable. It is possible that parameters in the CLIMEX model were not adequately adjusted and specifically diapause parameters were not included in the CLIMEX model. Studies indicate that *L. delicatula* diapauses in the egg stage (e.g., Dara 2015, Shim and Lee 2015). Finally, the CLIMEX model predicted that southern and eastern parts of India were suitable, whereas our MAXENT model predicted India is not suitable. We are not aware of any *L. delicatula* presence records originating from India and distribution maps show that tree of heaven is found only along a narrow strip of land in northern India (probably along the banks of the Ganges River) (Kowarik and Säumel 2007). Trapping and surveying of *L. delicatula* in this strip of land may reveal the pest is present in northern India.

One caveat of our study is that relatively large numbers of insect presence points were obtained from the introduced range instead of the native range. China is the native range of *L. delicatula* (Liu 1939, Zimian et al. 1997), while Korea, Japan, and the United States are introduced ranges. Here, the number of species records obtained from Korea, China, United States, and Japan were 126, 67, 45, and 2, respectively. Despite the relatively small number of presence data from China, the MAXENT predictions here are closely aligned with actual field occurrence of *L. delicatula* compared with

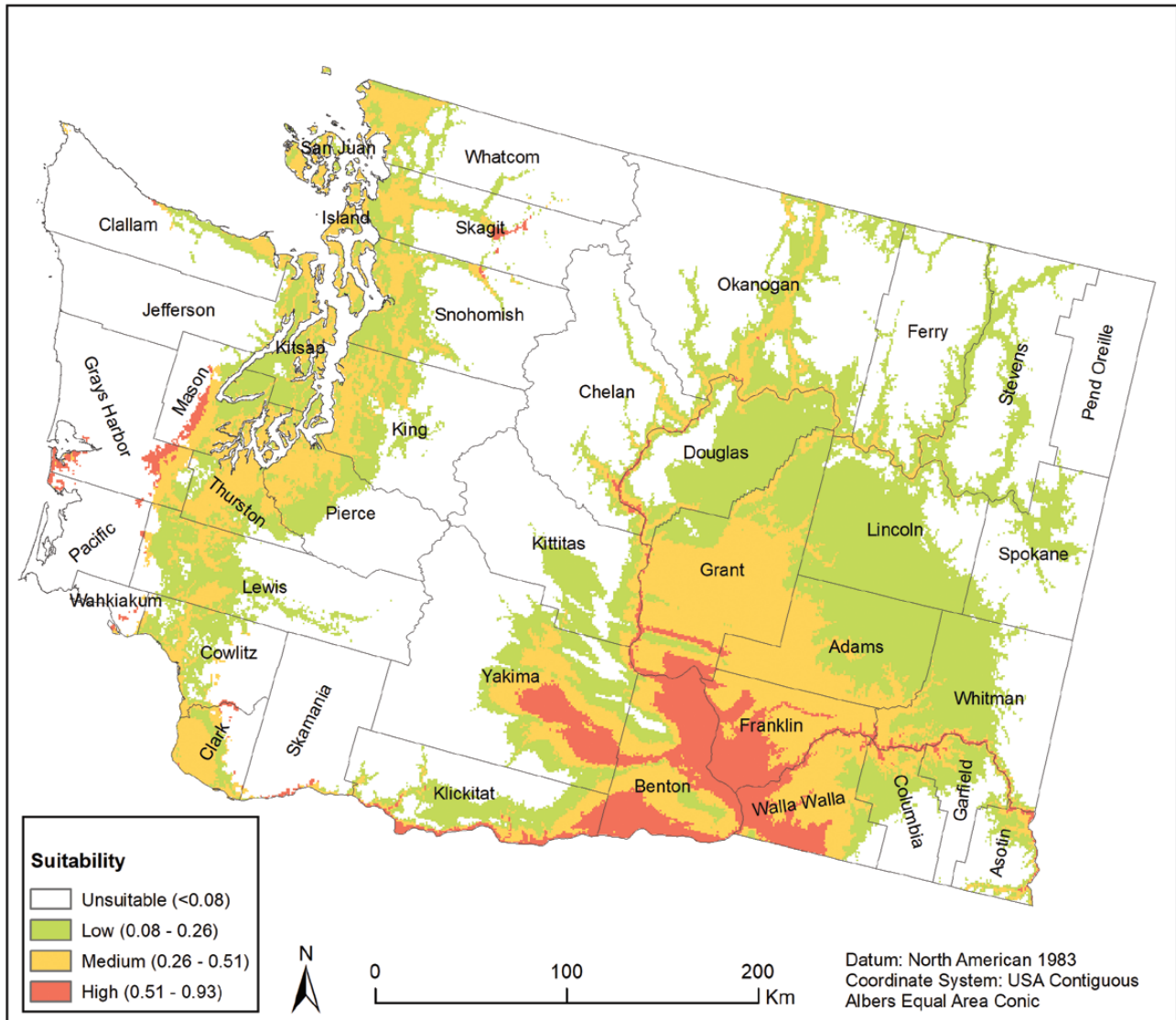


Fig. 4. Potential distribution of *L. delicatula* in WA, USA. Areas shaded in red, yellow, and green indicate high, medium, and low suitability, respectively. Unshaded/blank areas indicate areas that are unsuitable for *L. delicatula* establishment. Color figures are available in the online version only.

those predicted by CLIMEX (Jung et al. 2017). Unlike CLIMEX, the MAXENT model did not predict *L. delicatula* suitable habitats in Vietnam and we could not find presence records of the insect from Vietnam (within the presumed native range) (Hua 2000, Han et al. 2008), suggesting that perhaps *L. delicatula* is not well established there.

Distribution maps of tree of heaven indicate that the tree is present in northern Vietnam (Kowarik and Säumel 2007). Thus, we advise readers to interpret our prediction in Vietnam with caution, as more *L. delicatula* presence data (or lack thereof) are needed from different sites to improve the accuracy of our predictions. In addition, we caution readers where the environmental variables were dissimilar among the training dataset and the projection dataset (areas shown in hash marks; Fig. 2). These areas are mostly unsuitable habitats, for example, polar and tropical regions; however, we are uncertain if this is occurring for some sites, for example, northern India, because of our limited sampling.

In conclusion, we demonstrate that the MAXENT ENM approach can be effectively used to assess the establishment risk of *L. delicatula* in the United States and globally. Including biologically relevant variables such as degree-days in models improved the accuracy of our results. Moreover, evaluation tests performed on independent data indicated relatively high prediction accuracy, increasing our confidence in model results. Differences in prediction between CLIMEX (Jung et al. 2017) and MAXENT suggest that using comparative ENM techniques, gathering comprehensive data, and continuously updating model results are needed for the development of reliable pest establishment risk maps for emerging invasive pests such as *L. delicatula*. The risk maps developed in this study may be used for prioritizing *L. delicatula* surveying and trapping efforts. Proactive biosecurity measures including control of tree of heaven are needed to prevent the introduction and spread of *L. delicatula* into central and western U.S. states.

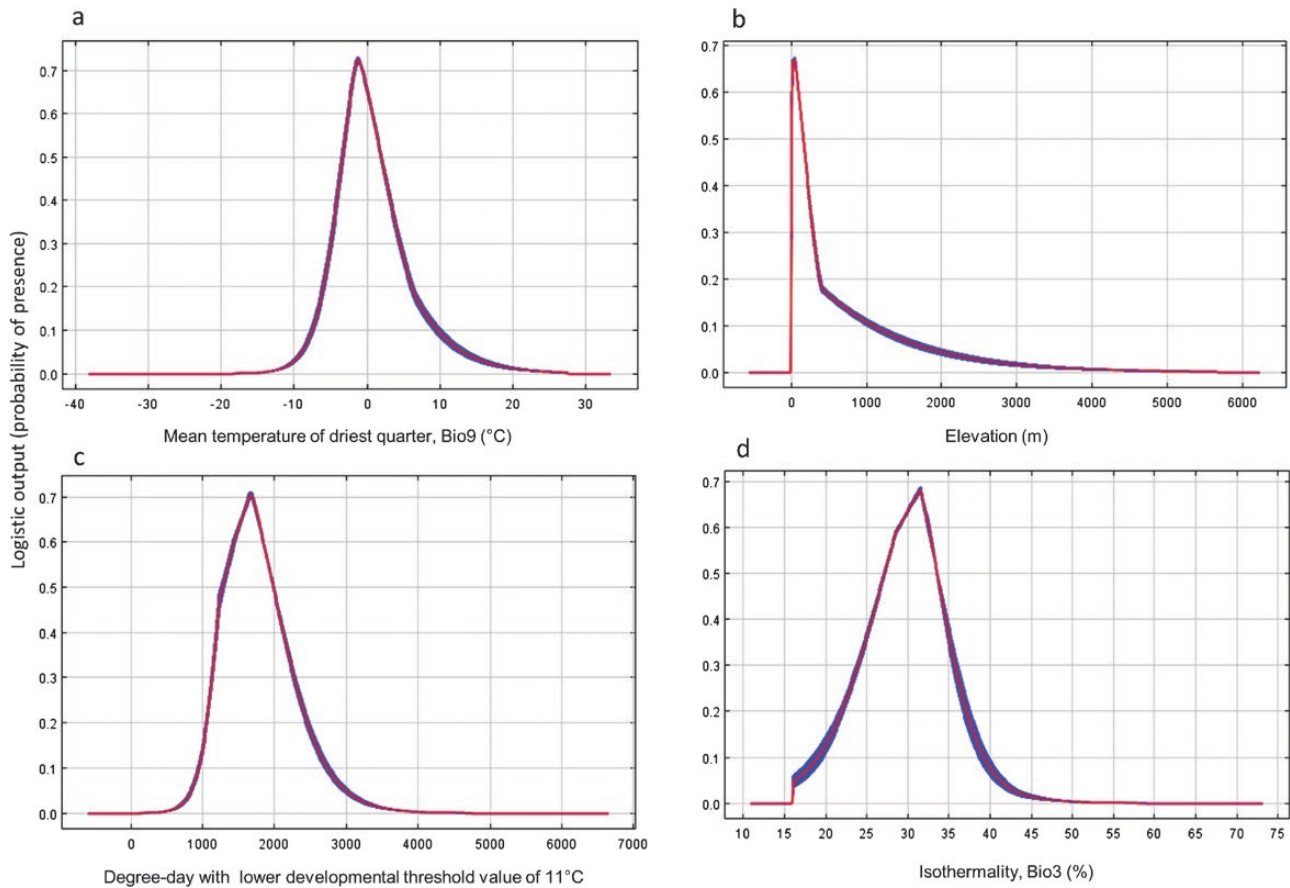


Fig. 5. Response curves of most important environmental variables used in the MAXENT model for predicting the potential distribution of *L. delicatula*. The MAXENT logistic output (probability of presence) is shown on the y-axis and the different environmental variables are shown on the x-axis.

Table 1. Percent contribution and permutation importance of environmental variables used in the MAXENT model for predicting the establishment risk of *L. delicatula*

Variable	Percent contribution	Permutation importance
Bio 9	47.7	25.5
Elevation	24.8	32.4
Degree-day	13.3	37.5
Bio 19	12.8	2.5
Bio 3	1.4	2.1

Bio 9 = Mean Temperature of Driest Quarter; Bio 19 = Precipitation of Coldest Quarter; and Bio 3 = Isothermality. Degree-day was calculated in ArcGIS using a lower developmental threshold value of 11°C.

Table 2. The 2018 production values (US \$) of apples, hops, cherries, grapes, and pears in Washington, Oregon, and California in the western United States

Commodity	Washington	Oregon	California
Apples	2,185,875,000	55,180,000	71,000,000
Hops	427,502,000	69,855,000	-
Cherries	426,470,000	70,835,000	140,395,000
Grapes	360,910,000	-	6,254,211,000
Pears	210,630,000	140,966,000	77,344,000
Sub Total	\$3,611,387,000	\$336,836,000	\$6,542,950,000
Grand Total =	\$10,491,173,000		

Source: National Agricultural Statistics Service (NASS 2018c in References Cited).

Acknowledgments

We thank Anne Nielsen, Rutgers University, NJ, USA for sharing *L. delicatula* presence points. We thank Kim Hoelmer, Javier Illan, and Surendra Dara for reviewing earlier drafts of the manuscript and two anonymous reviewers for providing useful comments that improved the manuscript. This research was funded by the USDA-ARS, CRIS project # 2092-22430-002-32-I. Mention of trade names or commercial products in this publication is solely for providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture. USDA is an equal opportunity provider and employer.

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