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Status and potential distribution of the Asian carpenter bee, *Xylocopa appendiculata* Smith (Apidae, Xylocopini), in the United States

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Abstract

We update the geographical distribution for *Xylocopa appendiculata* Smith, from eastern Asia, which was first reported from the United States of America (USA) in 2013. After the publication by Dahlberg et al. (2013), there have been more sightings supporting the establishment of *X. appendiculata* in northern California. We used plant hardiness zones and maximum entropy (Maxent) modeling to estimate the potential distribution of *X. appendiculata* in the USA using specimen data from multiple occurrences (confirmed data from literature, museum specimens and validated data from Discover Life.org and iNaturalist.org). We include images and a list of diagnostic features for the identification of the subgenus *Alloxylocopa* Hurd and Moure and the species *X. appendiculata* so that it can be identified and reported to corresponding state or federal authorities, if necessary.

Resumen

Se actualizan los datos de distribución de *X. appendiculata* Smith del este de Asia que fue reportada para los Estados Unidos de América por primera vez en 2013; después de este registro, se han presentado más avistamientos lo cual puede ser confirmación de que esta especie de hecho se ha establecido en el norte de California. Se utilizaron datos de "plant hardiness zones" (zonas de resistencias de plantas) y modelo de nichos Maxent para estimar la distribución potencial de esta especie en los EEUU mediante el uso de datos de especímenes de múltiples fuentes (datos confirmados de la literatura, ejemplares en museos y datos validados en Discover Life.org y iNaturalist.org) una distribución potencial de la especie en los EEUU con base en los datos de distribución original de la especie así como de datos en las bases de datos DiscoverLife.org y en la plataforma iNaturalist además de datos climáticos. Incluimos además imágenes y una lista de características diagnosticas del subgénero *Alloxylocopa* y de la especie *X. appendiculata* de manera que pueda ser identificada y reportada a las entidades federales o estatales en el futuro si es necesario.

Keywords
Biogeography, exotic bees, introduced species, invasive species, Maxent, Xylocopinae

Palabras claves
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Introduction

Bees of the genus *Xylocopa* Latreille are large and robust, 13–30 mm long (hence the common name of large carpenter bees), and are characterized, among other things, as having strongly sclerotized mouth parts (particularly the galeae), which are used to cut into corollas of tubular flowers to get the nectar (Sampson et al. 2004, Dedej and Delaplane 2004). Females of *Xylocopa* nest in wood, except those of subgenus *Proxylocopa* Hedicke which nest in the ground (Kronenberg and Hefetz 1984, Michener 2007).

Large carpenter bees have broad geographical distributions. They have diversified within tropical and subtropical regions and expanded their distributions to temperate regions (Hurd and Moure 1963). Several species of *Xylocopa* are suspected to have invaded oceanic islands, as only a few species exist within island groups and the distances between the original and their close relative's habitats are relatively short. For example, *Xylocopa sonorina* Smith was allegedly transferred by humans from North America to tropical Pacific islands, including Hawaii (Hurd 1958). More recently, Okabe et al. (2010) reported the introduction of the bamboo-nesting carpenter bee *Xylocopa tranquebarorum* (Swederus) in Japan. These authors also suspected that it was likely introduced from either India or China because of the characteristic mites associated with them. More recently, Dahlberg et al. (2013) reported *Xylocopa* a*ppendiculata* as introduced in California, United States.

Dahlberg et al. (2013) provided some diagnostic characteristics for the identification of *X. appendiculata* and some ways to separate it from native species in the USA. However, they used mostly coloration and the only picture in that paper is in black and white.

In this contribution, we provide information on the potential distribution of *X.* (*Alloxylocopa*) *appendiculata* in the USA. In addition, we include a diagnostic aid with images for the identification of the subgenus *Alloxylocopa* Hurd and Moure, and the species *X. appendiculata* and comments on its distribution, hosts, quarantine importance, and behavior.

Methods

The specimen used for the images and identification aids was collected in San Jose, California in 2012 and cited by Dahlberg et al. (2013). We also received from Mrs. Dahlberg images of males visiting the same garden in two different years (see new records in the results section) and we used them for some of the information provided in the diagnostic aids of the species. The female specimen used in the aids is housed at the California State Collection of Arthropods in the California Department of Agriculture (CDFA) building in Meadowview, Sacramento, California. Images were taken using a Nikon SMZ18 dissection microscope with a Nikon Digital Sight ds-fi2 camera attached. Once a series of 15–20 images per view were taken, they were focus stacked using the program Helicon Focus (Heliconsoft) and edited using Adobe Photoshop CS6.

Potential distribution modeling

To predict areas where *Xylocopa appendiculata* could establish in the USA, we used location data for specimens at the American Museum of Natural History (AMNH, Jerome Rozen and Lance Jones), The Snow Entomological Collection at the University of Kansas Biodiversity and Natural History Museum (SEMC, Jennifer Thomas), and verified distribution data from iNaturalist (2019), Discover Life (2019), and the Global Biodiversity Information Facility (GBIF 2019) for specimens ID validated by taxonomists. For the iNaturalist data, we used research grade detections, which are identifications that over 2/3 of the identifiers agree on (iNaturalist 2019). The combined dataset contained 325 *X. appendiculata* occurrences (duplicate records were removed). We also included in the analysis the type localities for *X. appendiculata* Smith, 1874 which is Ning-po-foo, China and *X. appendiculata circumvolans* (Smith, 1873) which is Hiogo, Japan (Appendix 1).

We used this dataset to predict where *X. appendiculata* could establish in the USA based on the associated Plant Hardiness Zones and Maxent niche modeling. We used two modeling approaches to increase the rigor of the analysis and better account for uncertainty regarding the bee's potential distribution in the USA.

The Plant Hardiness Zones are calculated based on the average annual extreme minimum temperature for an area in 10 °F (5.6 °C) increments (ARS 2012). They can be used to predict where plant pests (e.g., insects) could establish based on the Plant Hardiness Zones that match with the pest's native range (PERAL 2013). We overlaid the 325 *X. appendiculata* occurrence points with a Plant Hardiness Zone layer that was based on average climate data from 1988 to 2017 (Takeuchi et al. 2018). We then mapped the corresponding plant hardiness zones in the United States to predict its distribution.

We used maximum entropy niche modeling (Maxent 3.3.3k; Phillips et al. 2006, 2017) to estimate the potential distribution of *X. appendiculata* in the United States.

We removed duplicate records (>1 presence point within a ~4×4 km grid cell) and reduced spatial autocorrelation using 'spatial filtering' (i.e. reducing density of occurrences) using SDMToolbox (Brown 2014; Kumar et al. 2016). The total occurrences from the native range (Japan, Korean peninsula, and China) and invaded range (California, USA) were reduced from 325 to 158 (Appendix 1). We then calculated a Gaussian Kernel Density layer of occurrence data in ArcMap using SDMToolbox, which we used to account for potential sampling bias in occurrence data. We obtained climatic data from CHELSA website (Climatologies at High resolution for the Earth's Land Surface Areas; http://chelsa-climate.org/; Karger et al. 2017). We downloaded 19 bioclimatic variables data layers (~4×4 km spatial resolution) which represent average monthly temperature, precipitation, seasonal variables, and climatic extreme indices data from 1979–2013 (Hijmans et al. 2005; Appendix 2). We examined all 19 variables for cross-correlation (Pearson correlation coefficient, r) and highly correlated variables (|r| > 0.80) were excluded to reduce multicollinearity. The decision to exclude or include a variable was based on its potential biological relevance to *X. appendiculata* and its relative predictive power in the model (Appendix 2, 3).

Multiple models were fitted with different feature types and regularization multiplier values, and the best model with the optimal level of complexity was selected. Performance of the model was evaluated using the area under the receiver operating characteristic (ROC) curve (AUC; Peterson et al. 2011). We used the 10-fold cross-validation procedure for evaluating model performance, and reported averaged test AUC values across the ten replicates. Unsuitable areas for *X. appendiculata* were defined using the 100 percent sensitivity threshold (Liu et al. 2013). Therefore, areas with > 0.107 probability of presence in Maxent modeling results were considered as suitable for *X. appendiculata*.

Results

Potential distribution of *X. appendiculata* in the USA

The analysis of potential U.S. areas for *Xylocopa appendiculata* establishment based on plant hardiness zones (Figure 1) predicted that *X. appendiculata* could establish in Plant Hardiness Zones 5 to 10. This area includes most of the contiguous United States, and parts of southern and coastal Alaska (Figure 1). Colder regions like North Dakota, most of Alaska and the Rocky Mountains, and warmer regions like southern Florida and Hawaii were predicted to be unsuitable. *Xylocopa appendiculata*'s predicted cold hardiness is due to it's occurrence in colder parts of Japan.

The plant hardiness zone model likely represents a worst case scenario for *X. appendiculata*'s potential U.S. distribution due to the coarseness of the approach. This conclusion is supported by the fact that no western species of *Xylocopa* reach Canada, except for *X. virginica* which is present in the most southern parts of Ontario and Quebec.

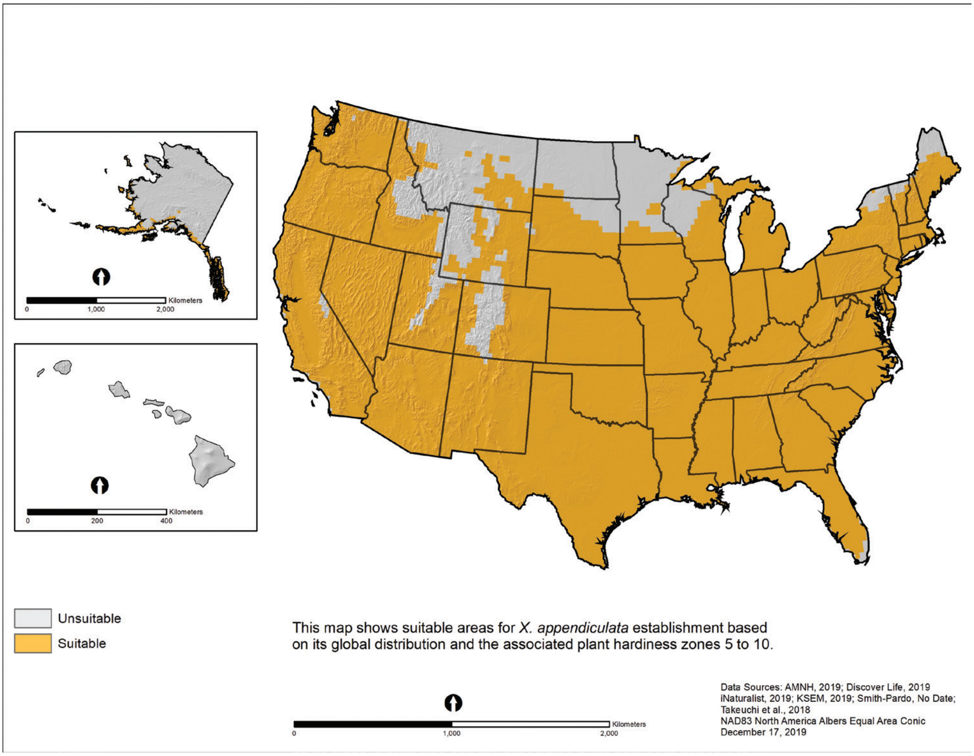

Figure 1. Suitable U.S. areas for *Xylocopa appendiculata* establishment based on plant hardiness zones – This map shows suitable areas for *X. appendiculata* establishment based on its global distribution and the associated plant hardiness zones 5 to 10.

The second analysis, or Maxent model, predicted climatically suitable areas for *X. appendiculata* in the eastern United States, parts of California, southwestern Alaska, and parts of Hawaii (Figure 2). Our model indicated medium to low climatic suitability (probability between 0.40–0.10) in parts of California, and very low suitability in Hawaii (probability 0.10–2.0) (Figure 2). The Maxent model for *X. appendiculata* performed well with a test AUC value of 0.98 (an AUC value of 1.0 indicates superior performance, and 0.5 indicates performance no better than random; Peterson et al. 2011). Precipitation of warmest quarter (Bio18) and temperature seasonality (Bio4) were the two top predictors associated *X. appendiculata*'s distribution, with 45% and 28% contributions, respectively (Appendix 2).

The climatic response curves fitted by the Maxent model suggest that areas with average annual temperatures (Bio1) between 4 °C and 22 °C, and average annual precipitation (Bio12) between 200 mm and 3,800 mm are likely suitable for *X. appendiculata* (Appendix 3). The distinct contrast in the patterns in predicted climatic suitability for *X. appendiculata* in northeastern Texas, Arkansas, northern Louisiana, western Mississippi and Tennessee, is probably due to variation in average summer

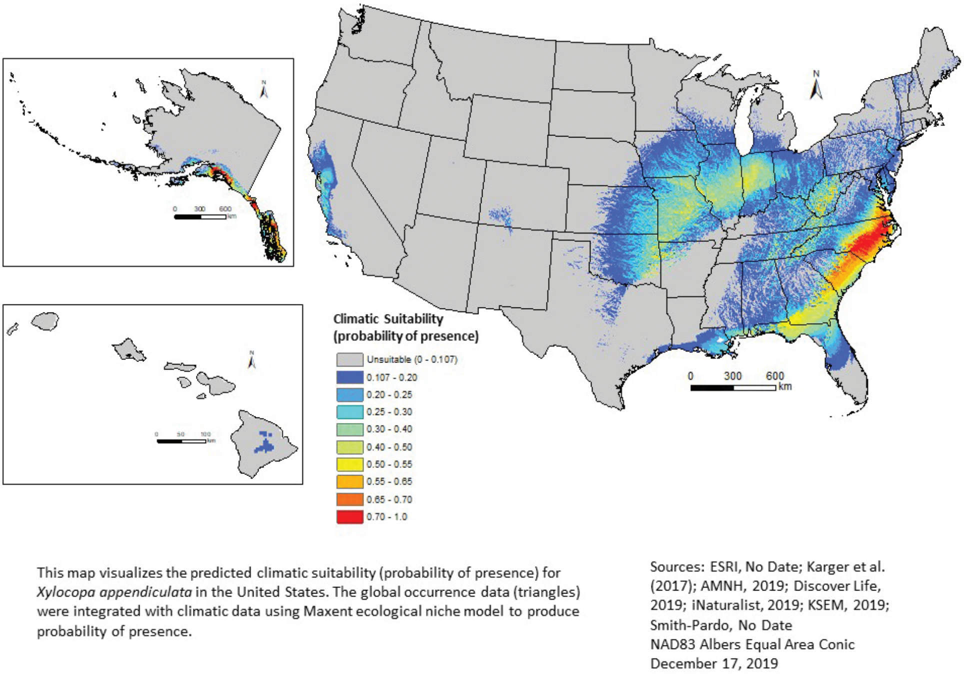

Figure 2. Predicted climatic suitability for *Xylocopa appendiculata* in the United States.

precipitation (June, July and August) in that part of the country (Appendix 4). Based on where the plant hardiness zone and Maxent models agree, the areas at greatest risk for *X. appendiculata* establishment include parts of southern Alaska and portions of eastern Virginia and the Carolinas (Figures 1, 2). Other at-risk areas include portions of western California and the eastern, north central, and central United States.

New observations and distribution records

USA records

USA. 1♀; California: San Jose; Sept. 2012; on flowers of *Salvia azurea* Michx. ex Lam. (Lamiaceae).1 ♂; same locality data; May 2013; on flowers of *Erysimum linifolium* (Pers.) J. Gay (Brassicaceae). 2♂; same locality data; Apr. 2015; on flowers *Erysimum linifolium* (Brassicaceae). 1♀; same locality data; Mar.2017; on flowers of *Prunus cerasifera* Ehrh (Rosaceae). 1♀; same locality data; May 2019; on flowers *Erysimum linifolium* (Brassicaceae).

USA. 1♀; California: Castro Valley; 37°42'13"N, 122°03'35"W; Sept. 2017; on flowers of *Grewia occidentalis* L. (Malvaceae). 1♀; same locality data; Aug. 2018; on flowers of *Passiflora* sp. L. (Passifloraceae). These two records show the movement of the species further north (~32–45 kilometers) from where the species was first reported in northern California.

Diagnostic aid for the identification of *Xylocopa appendiculata*

Bees of the subgenus *Alloxylocopa* Hurd and Moure (before the introduction of *X. appendiculata*, the subgenus was not known to be present in the Western hemisphere) can be distinguished from all other *Xylocopa* subgenera that are present in the USA and Canada by the following combination of characters: (*female*) pygidial plate without subapical spines (Fig. 3d, pp: pygidial plate), (*both sexes*) mesoscutellum with sub-horizontal dorsal surface abruptly and angulately separated from sub-vertical surface (Fig. 3e), postero-dorsal margin of mesoscutellum not surpassing posterior margin of metanotum and not projecting posteriorly beyond its posterior surface as a thin-edged flange., vertical fold of metasomal tergum 1 with foveate, hollow-like depression (Fig. 3f, arrow),

Specimens of *X. appendiculata* can be distinguished from native U.S. species of carpenter bees by the following combination of features: mandible with two teeth (Fig. 3g, arrow); clypeus and paraocular areas strongly punctate (Fig. 3b, square); occipital area, mesosoma and external side of fore tibiae with pubescence bright yellow, black on most of metasoma (Fig. 3a), except for few light brown setae close to pygidial plate

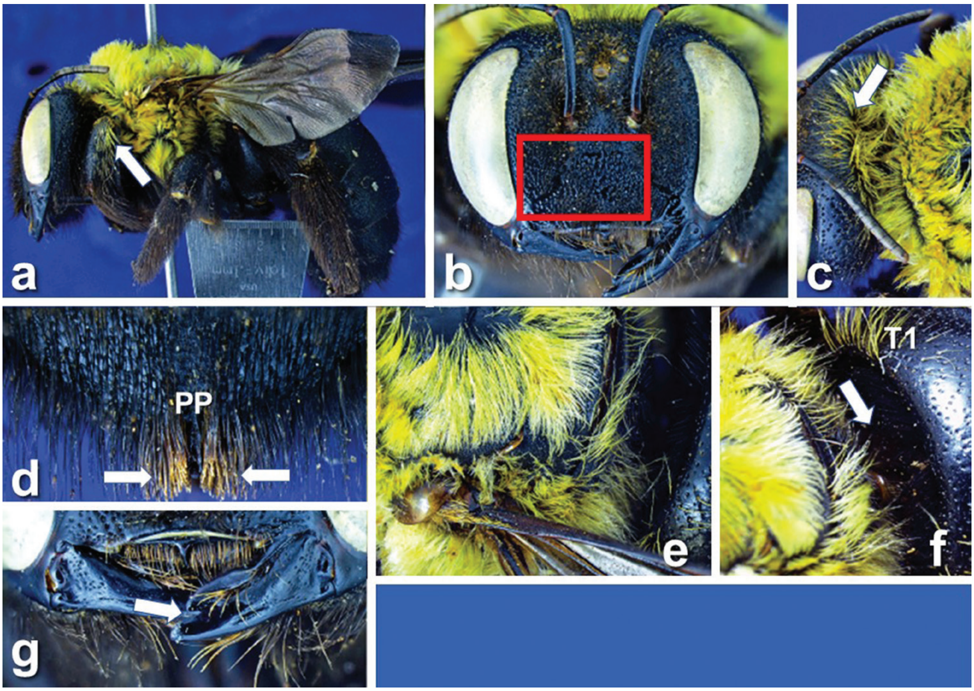

Figure 3. Some of the diagnostic features of *Xylocopa appendiculata* Smith: **a** lateral habitus showing coloration of pubescence on mesosoma and metasoma (the yellow coloration may not be as fluorescent in field specimens and is mostly due to reflections from the imaging system) **b** face showing integument sculpturing of clypeus and paraocular area **c** coloration of pubescence around occipital area (arrow) **d** pygidial plate (pp) and coloration of pubescence close to it (arrows) **e** shape of mesoscutellum from lateral view **f** Shape of metasomal tergum 1 (T1) from antero-lateral view and the presence of a foveate, hollowed like depression (arrow) **g** dentation of mandibles (arrow showing the two teeth on mandible).

on female (Fig. 3d, arrows); (Fig. 3c, arrow), Fig. 3a, e) and (Fig. 3a, arrow). The mesosoma of the native, North American species can be covered with black, grayish, brownish, or pale yellow setae and often have pale hairs elsewhere on the body and/or metallic highlights on the integument (Hurd and Moure 1963). The most similar of the native carpenter bees in the U.S. is *Xylocopa virginica* L. (the Eastern carpenter bee) which also has two mandibular teeth and a strongly punctuate clypeus, but differs from *X. appendiculata* because it lacks the extensive bright yellow hairs in the mesosoma and vertex. The males of *X. appendiculata* also lack the extensive bluish or greenish reflections of the body present in males of *X. virginica*.

Floral hosts

Little is known about the preferred plants visited and pollinated by *X. appendiculata* in its native range, but based on the observations of visits in the USA this species seems, at least potentially, polylectic in its floral preferences. In the new habitat in the Bay Area this species was seen visiting flowers of introduced plants such as *Grewia occidentalis* (originally from Africa) and *Passiflora* sp. (originally from tropical America). Both plants were in the senior author's bee garden in Castro Valley, CA.

Discussion

Dahlberg et al. (2013) provided a list of all the U.S. species of *Xylocopa* and their distributions by the state. The potential distribution maps show that *X. appendiculata* could establish in all the states where native species of carpenter bees occur according to the distribution records in literature. This is especially true in the east coast where it could broadly overlap with the common species *X. virginica*. Due to their morphological similarities successful diagnosis would require careful examination and the use of the diagnostic aids provided here.

As with all new introduced species, there is a risk that *X. appendiculata* will be better at competing for foraging plants and nesting sites (dry or rotten wood), which may limit resources for native bees. In addition, carpenter bees can be a nuisance because they can nest in human made structures such as fences and roofs. Due to their large size, females of *X. appendiculata* can also damage flowers while feeding without pollinating them.

There is evidence of introduced carpenter bees bringing new parasites (and possibly diseases) to invaded areas (Okabe et al. 2010; Kontschán et al. 2016). There may be new parasites associated with this species that do not occur in the USA that can be potentially damaging to our native *Xylocopa* species.

As is the case with other wood nesting bees that have been introduced into the USA, *X. appendiculata* will likely compete with native species for empty nesting sites or even usurp them when sites are limited (Mangum and Brooks 1997; Batra 1998; Laport and Minckley 2012).

In addition, *Xylocopa appendiculata* also nests in wood, twigs and large stalks of dead plants commonly used to make shipping crates and woodcrafts, which could increase its rate of spread over long distances and across natural barriers such as oceans and mountain ranges.

Given *X. appendiculata*'s potential to establish in the United States and outcompete native carpenter bees it is important to continue monitoring its spread. In this regard, our analysis can assist with *X. appendiculata* identification and informing surveys.

Acknowledgements

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Appendix 1

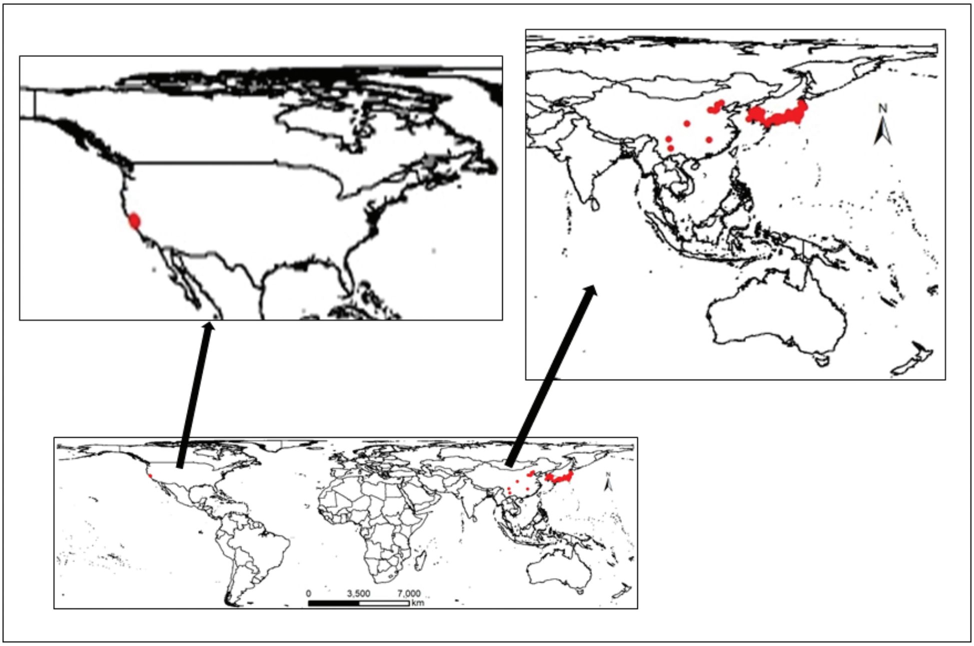

Figure A1. Global distribution of *Xylocopa appendiculata* based on specimens deposited in collections and confirmed records on iNaturalist, GBIF, and Discover Life.org (red circles).

Appendix 2

Table A1. Relative importance of 19 climatic variables considered in *Xylocopa appendiculata* Maxent model. Bold shows the variables used in the Maxent model; other variables were dropped because of high cross-correlations or lower predictive power in the model. Presented values are averages for 10 replicate runs.

Variable	Percent contribution
Precipitation of warmest quarter (Bio18; mm)	**45.3**
Temperature seasonality (SD x 100) (Bio4)	**27.9**
Mean annual precipitation (Bio12; mm)	**15.0**
Mean temperature of driest quarter (Bio9; °C)	**6.0**
Precipitation of driest month (Bio14; mm)	**4.5**
Precipitation seasonality (CV) (Bio15)	**1.2**
Annual mean temperature (Bio1; °C)	–
Mean diurnal range in temperature (Bio2; °C)	–
Isothermality (Bio3)	–
Maximum temperature of warmest month (Bio5; °C)	–
Minimum temperature of coldest month (Bio6; °C)	–
Temperature annual range (Bio7; °C)	–
Mean temperature of wettest quarter (Bio8; °C)	–
Mean temperature of warmest quarter (Bio10; °C)	–
Mean temperature of coldest quarter (Bio11; °C)	–
Precipitation of wettest month (Bio13; mm)	–
Precipitation of wettest quarter (Bio16; mm)	–
Precipitation of driest quarter (Bio17; mm)	–
Precipitation of coldest quarter (Bio19; mm)	–

Appendix 3

Table A2. Pearson correlation (r) among the six best predictors in the *Xylocopa appendiculata* Maxent model; see Appendix1 for variable names.

	Bio4	Bio9	Bio12	Bio14	Bio15
Bio9	-0.787				
Bio12	-0.568	0.289			
Bio14	-0.265	0.085	0.732		
Bio15	-0.133	0.254	-0.298	-0.527	
Bio18	-0.241	-0.030	0.727	0.593	-0.273

Appendix 4

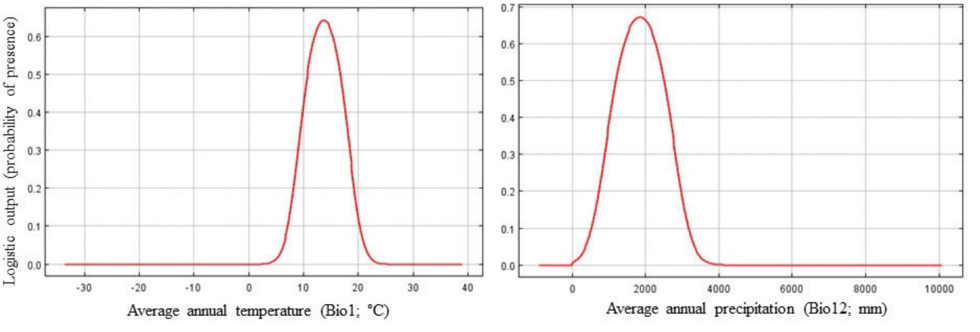

Figure A2. Climatic variables' response curves fitted by Maxent model for *Xylocopa appendiculata*.

Appendix 5

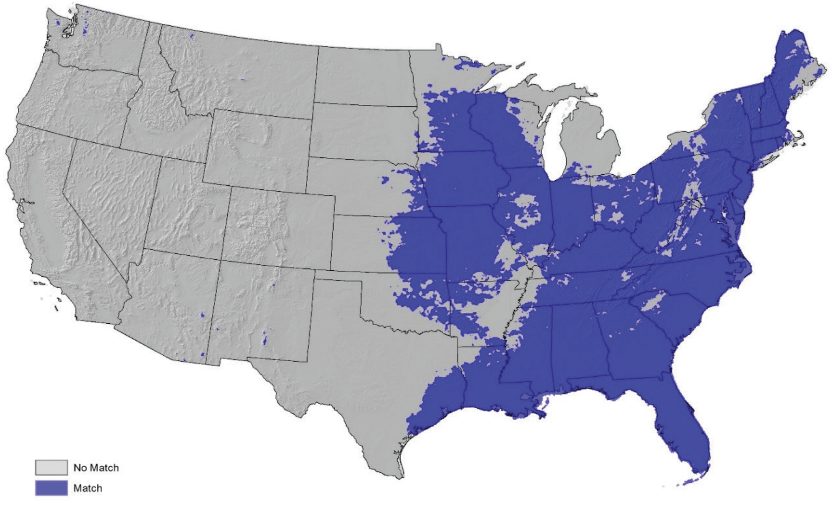

Figure A3. Summer Precipitation Patterns in the USA: Average summer precipitation (June, July and August) was calculated using PRISM climate data with the Spatial Analytic Framework for Advanced Risk Information Systems (SAFARIS 2019). Areas with ≥ 300 mm of precipitation between June and August (blue) based on average data from 2000 to 2019.