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Maximum Entropy (MaxEnt) Modeling of the Potential Distribution of *Aspidiotus rigidus* Reyne (Hemiptera: Diaspididae) in the Philippines

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The coconut scale insect (CSI) *Aspidiotus rigidus* Reyne (Hemiptera: Diaspididae) poses a significant threat to coconut production in the Philippines as shown by recent outbreaks. Ecological niche modeling using Maximum Entropy (MaxEnt) was used to determine the effects of environmental factors on the infestation of *A. rigidus*, and map its potential distribution in the Philippines to assess the risk of future outbreaks. The influence of bioclimatic variables on *A. rigidus* infestation was determined using MaxEnt modeling using the location data of *A. rigidus* occurrence confirmed using molecular markers. Rainfall and temperature variables were important for *A. rigidus* distribution with rainfall being more important than temperature. Annual rainfall and precipitation seasonality were the first and second most important variables determining *A. rigidus* infestation with 47.9% and 30.7% permutation importance, respectively. The final *A. rigidus* MaxEnt model showed an area under the curve (AUC) value of 0.93 indicating a very good predictive power; hence, the potential distribution map can be used to assess the risk of *A. rigidus* outbreaks in the Philippines.

Key Words: *Aspidiotus rigidus* Reyne, coconut scale insect, insect outbreak, Maximum entropy modeling

Abbreviations: CSI– coconut scale insect, MaxEnt – maximum entropy, ROC—receiver operating characteristic, AUC—area under the curve

INTRODUCTION

Maximum entropy (MaxEnt) is a general purpose machine learning method that estimates a target probability distribution based on the distribution of maximum entropy (closest to uniform) considering constraints based on incomplete information of the target species (Phillips et al. 2006). MaxEnt modeling finds the maximum entropy probability distribution to predict the potential distribution of a target species through the analysis of the location data of the target species depending on the influence of environmental variables. Location data can be obtained from distribution data such as those from field surveys, while the environmental variables can include climatic, topographic and edaphic variables (Phillips and Dudik 2008). MaxEnt is suited for modeling the geographical distribution of a target species based on presence only data (Phillips et al. 2006). MaxEnt is a generative approach, rather than a discriminative approach, that uses environmental data across the study area, which is advantageous when presence data is limited (Phillips and Elith 2013).

The coconut scale insect (CSI) pest, *Aspidiotus rigidus* Reyne (Hemiptera: Diaspididae) posed a significant quarantine threat to coconut-producing countries worldwide (Watson et al. 2015). The CSI infestation by *A. rigidus* stops photosynthesis resulting to yellowing, then drying of the leaves, and the coconut tree dies in 6 months or less (Reyne 1948; Watson et al. 2015). The devastating CSI outbreak from 2009-2014 in Cavite, Laguna, Batangas, and Quezon provinces posed a serious threat to the Philippine coconut industry (Watson et al. 2015; Eusebio 2016). Another CSI outbreak occurred in Basilan and Zamboanga in Mindanao from 2013-2018 (Carbayas 2013; Colina 2017; Caoili et al. 2018). The cause of these CSI outbreaks was morphologically identified as *Aspidiotus rigidus* Reyne, an introduced CSI species (Caoili et al. 2015; Watson et al. 2015) and later confirmed using molecular markers (Caoili et al. 2015; Serrana et al. 2019; Guerrero et al. 2020).

Historical accounts of the occurrence of *A. rigidus* in the Philippines have been scarce but a recent study on the genetic structure of *A. rigidus* has indicated significant insights on the causal factors that triggered the CSI outbreaks in CALABARZON, Basilan, and Zamboanga. Lever (1969) stated that *A. rigidus* may have been found in the Philippines but there were no details provided, while Velasquez (1971) stated that *A. rigidus* may have been confined in the southern parts of the Philippines. Serrana et al. (2019) unravelled the genetic structure of the CSI outbreaks from 2014-2017 in the northern (Laguna, Bataan, and Batangas provinces) and southern (Basilan and Zamboanga Peninsula) regions of the Philippines that showed a clear differentiation among the *A. rigidus* populations in the northern and southern regions of the Philippines but there is very low or no genetic differentiation within and among the populations per geographic region. These results implied that the CSI outbreaks in the northern and southern regions are unrelated events. Furthermore, the authors stated that the CSI outbreak in the northern region may have been due to a recent introduction of a non-native *A. rigidus* population given the lack of historical information, but the CSI outbreak in the southern region may be due to resurgence of an established *A. rigidus* population given that the *A. rigidus* population in the southern region is older than that in the northern region. This resurgence can be due to sudden climatic changes or anthropogenic habitat imbalance.

This study aims to identify the environmental (bioclimatic) determinants of *A. rigidus* infestation and map the potential distribution of *A. rigidus* in the Philippines using MaxEnt modeling. The potential distribution can be used to assess the risk of *A. rigidus* outbreaks in the Philippines in order to guide quarantine protocols and CSI management strategies. In entomology, several studies have successfully used MaxEnt to determine environmental determinants and map the potential distribution of insect pests (e.g. Kumar et al. 2014; Kim et al. 2015).

MATERIALS AND METHODS

Presence Only Data

Presence-only data for this study were collected during 2014-2018 from different outbreak locations in the following provinces in the country viz. Laguna, Bataan, Batangas, Quezon, Basilan, Zamboanga Peninsula, Marinduque, Romblon, and Albay following the sampling and morphological and molecular identification procedures of Caoili et al. (2015) and Guerrero et al. (2020). Geographical coordinates of locations of sampling points with confirmed presence of *A. rigidus* were used in developing the MaxEnt model in this study (Fig. 1; Supplemental Table 1). Coconut leaf samples infested with coconut scale insects were obtained from these sampling locations and identified as *A. rigidus* using molecular markers (B.L. Caoili, unpublished *A. rigidus* distribution database).

Climatic Data

Monthly rainfall and temperature data from 2014-2018 were downloaded from TerraClimate (http://www.climatologylab.org/terraclimate.html) database. TerraClimate is a high spatial resolution (~4 km) monthly climatic database for global terrestrial surface developed by combining different sources of monthly climatic datasets across the globe. These data sets include precipitation, maximum and minimum temperature, wind speed, vapor pressure, and solar radiation

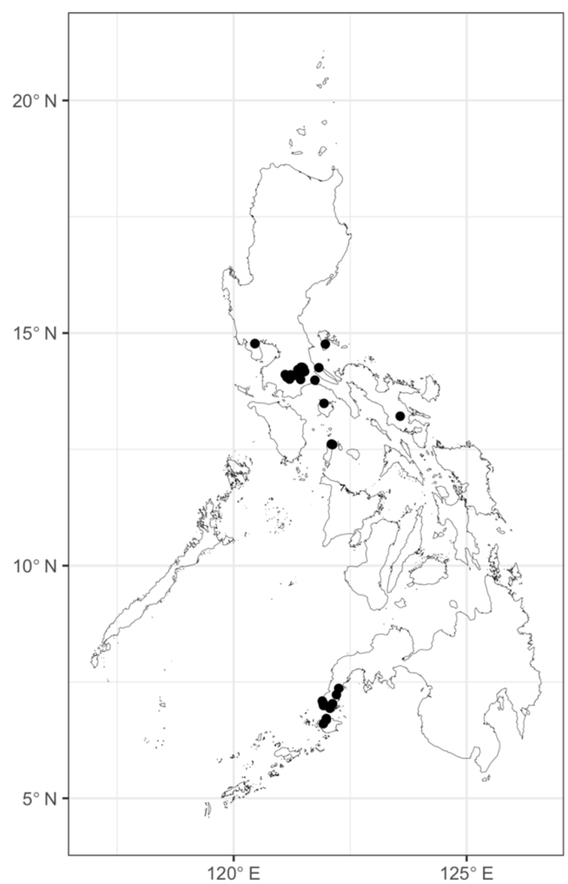

Fig. 1. Location map of *Aspidiotus rigidus* Reyne sampling points in the Philippines.

Supplemental Table 1. Geographical coordinates of locations with confirmed occurrence of *Aspidiotus rigidus* Reyne from 2014-2018 used in Maximum Entropy modeling (B.L. Caoili, unpublished *A. rigidus* distribution database).

Location	Year of Collection	GPS Coordinates (decimal degrees)	
		Longitude	Latitude
Bay, Laguna	2014	121.224230	14.102074
Malvar, Batangas	2014	121.142366	14.050913
Polillo, Quezon	2014	121.967043	14.763357
Orani, Bataan	2014	120.455056	14.772444
Balanga, Bataan	2014	120.457472	14.774417
Magdalena, Laguna	2014	121.425750	14.217167
Magdalena, Laguna	2014	121.427611	14.181083
Candelaria, Quezon	2014	121.436639	14.002639
Liliw, Laguna	2014	121.442333	14.123139
Tanauan, Batangas	2014	121.107222	14.107222
San Pablo, Laguna	2014	121.373722	14.112361
San Pablo, Laguna	2014	121.279972	14.085278
Pila, Laguna	2014	121.376833	14.212100
Sta. Cruz, Laguna	2014	121.394806	14.220417
Sta. Cruz, Laguna	2014	121.444972	14.265000
Pagsanjan, Laguna	2014	121.475889	14.262417
Cavinti, Laguna	2014	121.497139	14.241778
Luisiana, Laguna	2014	121.511306	14.182750
Luisiana, Laguna	2014	121.511083	14.182028
Luisiana, Laguna	2014	121.524194	14.173472
Sabang, Quezon	2016	121.827568	14.255557
Zamboanga City	2016	121.930833	7.033306
Zamboanga City	2016	121.917028	70.043000
Zamboanga City	2016	121.949639	6.998889
Isabela, Basilan	2016	121.984472	6.690306
Zamboanga City	2016	121.942472	7.009389
Lantawan, Basilan	2016	121.925417	6.602944
Isabela, Basilan	2016	121.987306	6.686861
Isabela, Basilan	2016	121.984611	6.690250
Malvar, Batangas	2017	121.148433	14.055550
Sto. Tomas, Batangas	2017	121.198733	14.009433
Mogpog, Marinduque	2017	121.939050	13.487767
Cabolutan, Romblon	2018	122.102317	12.611983
Cabolutan, Romblon	2018	122.096667	12.612550
Cabolutan, Romblon	2018	122.100717	12.612083
Cabolutan, Romblon	2018	122.123333	12.602050
Lucena, Quezon	2018	121.743288	13.987906
Isabela, Basilan	2018	121.989150	6.714243
Zamboanga City	2018	122.065598	6.934506
Zamboanga City	2018	122.121898	7.032429
Zamboanga City	2018	122.254465	7.362275
Zamboanga City	2018	121.927924	6.993437
Zamboanga City	2018	122.205129	7.226174
Zamboanga City	2018	121.902236	7.090272
Guinobatan, Albay	2018	123.574044	13.212591

(Abatzoglou et al. 2018). Five bioclimatic variables were derived from these data sets following the methodology of O'Donnell and Ignizio (2012). These variables were the following: 1) annual precipitation, 2) precipitation seasonality, 3) annual mean temperature, 4) temperature seasonality, and 5) annual mean diurnal range. Table 1 shows the complete description and formula on deriving these bioclimatic variables.

MaxEnt Modeling

In the MaxEnt modeling of *A. rigidus*, presence-only data were split into 80:20 for training and test/validation data sets, respectively. Thirty-six data points were assigned as training points and 9 data points were assigned as test/validation points. MaxEnt is relatively robust to small sample sizes (Pearson and Dawson 2007), and it performs better than other ecological niche modeling methods with a small sample size (Wisz et al. 2008). Meanwhile, 1000 data points were randomly generated for the entire country to serve as background points. MaxEnt uses background points (points where presence or absence is not measured) that contrast against the occurrence points (presence locations) in order to estimate the probability of occurrence (Merow et al. 2013). The MaxEnt model was run using R statistical software (Ihaka and Gentleman 1996) via dismo package (Hijmans et al. 2016).

The predictive ability of the MaxEnt model was evaluated using the area under the receiver operating characteristic (ROC) curve values. ROC curve plots the performance of the model and AUC is the area under the curve (Rodder et al. 2009). AUC provides a single measure of model performance, which is independent of any threshold (Phillips et al. 2006). AUC ranges from: 0.5 (random or no predictive ability); 0.7-0.8 (usable model); 0.8-0.9 (good model performance); and 0.9-1.0 (very good predictive power) (Rodder et al. 2009). The output of MaxEnt is a map showing an estimate of habitat suitability or risk of invasion for *A. rigidus* in the Philippines varying from 0 (lowest) to highest (1).

Table 1. Bioclimatic data used for modeling *Aspidiotus rigidus* Reyne using Maximum Entropy.

Bioclimatic Variable	Description*	Unit
Annual rainfall (precipitation) (AP)	Sum of all total monthly precipitation values	mm
Precipitation seasonality (PS)	Measure of the variation in monthly precipitation totals over the course of the year	%
Annual mean temperature (AMT)	Annual mean temperature	°C
Temperature seasonality (TS)	Amount of temperature variation over a given period based on the ratio of the standard deviation of the monthly mean temperatures to the mean monthly temperature	%
Annual mean diurnal range (AMDR)	Mean of the monthly temperature ranges (monthly maximum minus monthly minimum).	°C

*Descriptions of bioclimatic variables were adopted from O'Donnell and Ignizio (2012).

RESULTS AND DISCUSSION

MaxEnt Model Selection

In the *A. rigidus* model selection, four environmental (bioclimatic) variables were included in the developed final model (Table 2). Annual rainfall had the highest permutation importance of 47.9%. Precipitation seasonality (coefficient of variation) had the second highest permutation importance of 30.7%. Annual average temperature showed the third highest permutation importance of 17.7%. Annual mean diurnal range based on mean monthly temperature ranges (maximum temperature – minimum temperature) had the lowest permutation importance of 3.8%.

Among the environmental variables included in the model, mean diurnal range showed a decreasing probability of occurrence as the variable increased, while annual rainfall, annual mean temperature, and precipitation seasonality indicated an increasing phase followed by a decreasing trend of the curve of probability. For annual rainfall, the probability of occurrence of 0.54 was observed at 1000 mm of rainfall, which then increased to 0.77 at 2200 mm and decreased up to about zero probability at 500 mm (Fig. 2a). For seasonality of precipitation, zero probability of occurrence was estimated at 10-20% coefficient of variation (CV) and it increased up to 0.65 at about 65% CV, and then it decreased to 0.08 probability at 140% CV (Fig. 2b). For annual mean temperature, the probability increased from 0 to 0.62 at 27°C and decreased to 0.22 at 29-39°C (Fig. 2c). High probability of occurrence was estimated at low values of mean diurnal range with the highest probability of 0.82 occurring at 5.2 to 5.9°C; but then, the probability decreased up 0.575 to 8.5-10°C (Fig. 2d).

Environmental Conditions Affecting the Species Distribution of *A. rigidus*

The bioclimatic variables used in MaxEnt modeling are biologically relevant to understand species responses to climate. Annual mean temperature approximates the total energy inputs for an ecosystem. Annual diurnal range captures diurnal temperature range, which can indicate

Table 2. Permutation importance of bioclimatic variables included in the Maximum Entropy model of *Aspidiotus rigidus* Reyne.

Bioclimatic Variable	Permutation Importance (%)
Annual rainfall (precipitation) (AP)	47.4
Precipitation seasonality (PS)	30.7
Annual mean temperature (AMT)	17.7
Annual mean diurnal range (AMDR)	3.8

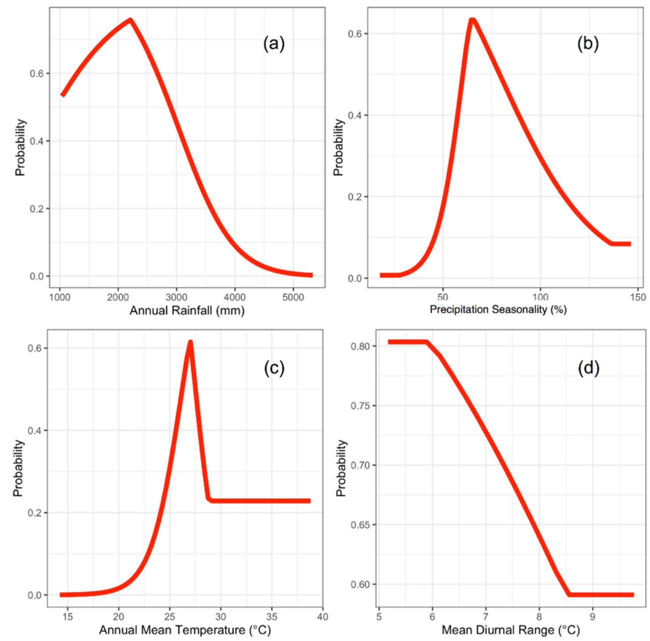

Fig. 2. Response curves of *Aspidiotus rigidus* Reyne occurrence with respect to (a) annual rainfall (precipitation), (b) precipitation seasonality, (c) annual mean temperature, and d) annual mean diurnal range.

the relevance of temperature fluctuation for different species. Annual total rainfall indicates the importance of water availability to the species distribution, while rainfall seasonality provides a percentage of rainfall variability where larger percentages represent greater rainfall variability (O'Donnell and Ignizio 2012). The effects of the four bioclimatic variables included in the final *A. rigidus* MaxEnt model on CSI biology are interpreted as follows.

Rainfall variables are important for *A. rigidus* distribution. Annual rainfall and precipitation seasonality are the first and second most important variables, respectively, in the *A. rigidus* MaxEnt model. The effect of rainfall can be related to moisture in the coconut canopy because *A. rigidus* thrives in high relative humidity. In Sangi Island, Indonesia, where an outbreak occurred in the 1920s, *A. rigidus* colonized the humid valleys first and infestations on hill ridges were less intense than in the lower valley areas (Reyne 1948). Interestingly, in a study by Almarinez et al. (2020), precipitation seasonality had the highest relative contribution to the MaxEnt model of *Comperiella calauanica*, a native encyrtid parasitoid of *A. rigidus*. Since *C. calauanica* has always been found to occur together with its host *A. rigidus*, the authors of this study stated that their MaxEnt model can be used to predict suitable areas for *A. rigidus* infestation.

Temperature has an important effect on *A. rigidus* distribution. Annual mean temperature and annual mean diurnal range or the mean of the monthly temperature ranges (monthly maximum minus monthly minimum) were the third and fourth variables included in the final model based on permutation importance. Reyne (1948) found that the life cycle duration of *A. rigidus* decreased by 17% with a 2.2°C increase in air temperature; thus, a faster growth and development cycle of *A. rigidus* can occur at higher temperatures. Niega (2019) used a fuzzy logic approach to evaluate the effects of weather on CSI infestation by *A. rigidus* in Batangas province from 2012-2014 that showed temperature had the largest impact in the infestation followed by wind speed and relative humidity.

Predicted Potential Distribution of *A. rigidus*

The final MaxEnt model of *A. rigidus* showed an AUC value of 0.93, indicating a very good performance. This also implies a model with high predictive power (Rodder et al. 2009; Peterson et al. 2011). High risks of *A. rigidus* infestation are indicated as probability of suitability ranging from 0.75 to 1.0 in the following locations: Northern Cagayan; parts of Isabela; Laguna, Batangas, Rizal and Quezon; northern Occidental Mindoro; Palawan; Marinduque; parts of Davao de Oro; Zamboanga Peninsula; and parts of Basilan. Medium risks of *A. rigidus* infestation indicated as probability of suitability ranging from 0.5 to 0.74 are shown in Ilocos Norte, Cagayan, Isabela; Central Luzon; Polillio Island, Cavite; Camarines Sur; western Albay, Romblon; Mindoro; Masbate; Southern Iloilo and Guimaras; parts of Negros Oriental, Misamis Oriental; Davao de Oro, Davao Oriental, Zamboanga Peninsula, and Basilan (Fig. 3). Furthermore, all the observed locations in the distribution of *A. rigidus* in the Philippines reported by Watson et al. (2015), which were based on visual observations, reports and/or examined specimens, are predicted by this *A. rigidus* MaxEnt model.

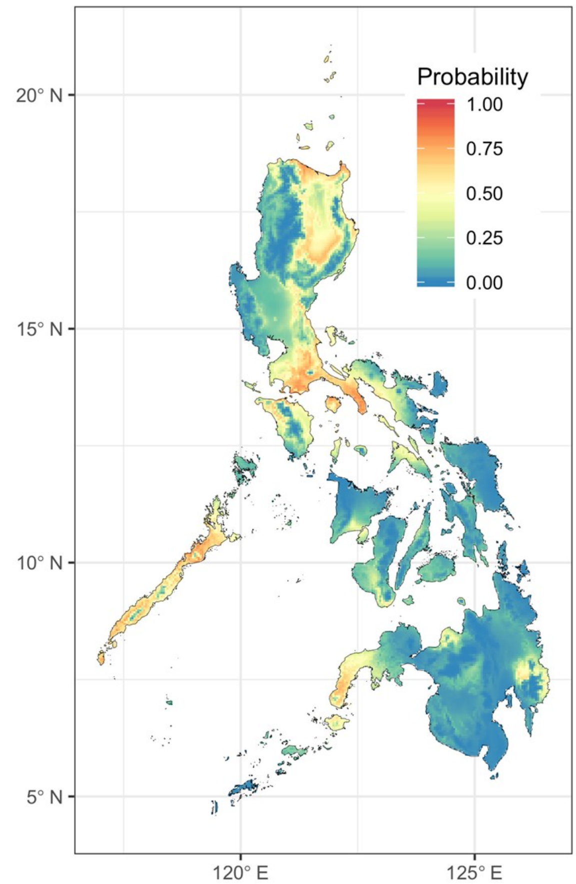

Fig. 3. Predicted distribution of *Aspidiotus rigidus* Reyne in the Philippines using the Maximum Entropy model.

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