



# A Bioclimate-Based Maximum Entropy Model for *Comperiella calauanica* Barrion, Almarinez & Amalin (Hymenoptera: Encyrtidae), Parasitoid of *Aspidiotus rigidus* Reyne, in the Philippines

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## Abstract

**Background:** *Comperiella calauanica* Barrion, Almarinez & Amalin (Hymenoptera: Encyrtidae) is a host-specific endoparasitoid and effective biological control agent of *Aspidiotus rigidus* Reyne (Hemiptera: Diaspididae), whose outbreak in 2010 to 2015 severely threatened the coconut industry in the Philippines. Using the maximum entropy (MaxEnt) algorithm, we developed a Species Distribution Model (SDM) for *C. calauanica* based on 19 bioclimatic variables, using occurrence data obtained mostly from field surveys conducted in *A. rigidus*-infested areas in Luzon Island from 2014 to 2016.

**Results:** The calculated AUC values for the model were very high (0.966, standard deviation=0.005), indicating the model's high predictive power. Precipitation seasonality was found to have the highest relative contribution to model development. Response curves produced by MaxEnt suggested the positive influence of mean temperature of the driest quarter, and negative influence of precipitation of the driest and coldest quarters on habitat suitability.

**Conclusion:** Given that *C. calauanica* has been found to always occur with *A. rigidus* in Luzon Island due to high host-specificity, the SDM for the parasitoid may also be considered and used as a predictive model for its host. This was confirmed through field surveys conducted between late 2016 and early 2018, which found and confirmed the occurrence of *A. rigidus* in three areas predicted by the SDM to have moderate to high habitat suitability or probability of occurrence of *C. calauanica*: Zamboanga City in Mindanao; Isabela City in Basilan Island; and Tablas Island in Romblon. This validation in the field demonstrated the utility of the bioclimate-based SDM for *C. calauanica* in predicting habitat suitability or probability of occurrence of *A. rigidus* in the Philippines.

**Keywords:** Maximum Entropy; Species Distribution Modeling; *Comperiella Calauanica*; *Aspidiotus Rigidus*; Pest Invasion Forecasting

## Introduction

The Philippines is a primarily agricultural nation in Southeast Asia, despite rapid industrialization in many areas of the archipelago. Statistics in 2015 indicate that 29.15% of total employment in the Philippines is in agriculture [1]. The agricultural sector has provided the fourth highest contribution to the country's Gross Domestic Product (GDP), with the latest data summarized by the Philippine National Statistics Coordination Board indicating GDP from agriculture at 53.7 billion Philippine pesos (equivalent to about 1 billion US dollars). Coconut is one of the high value commercial crops of the country and has been recognized for years as a top agricultural export [2]. However, production of this crop was severely threatened by an outbreak of the destructive coconut scale, *Aspidiotus rigidus* Reyne (Hemiptera: *Diaspididae*), which devastated plantations in the Southern Tagalog region of Luzon Island from 2010 to 2015. Feeding of this diaspidid on the foliage of coconut palms has been found to impair photosynthesis, consequently affecting flowering, fruiting, and even compromising the survival of the infested tree [3]. A native parasitic wasp belonging to genus *Comperiella* Howard (Hymenoptera: *Encyrtidae*) was subsequently discovered and was found to be highly and very specifically parasitizing *A. rigidus* in the outbreak areas from 2014 onwards. Preliminary findings and observations from field and laboratory studies suggested the potential of the parasitoid for biological control [4]. Additionally, the encyrtid was not only the first native record in the Philippines for its genus, but was also described as a new species, *C. calauanica* Barrion, Almarinez & Amalin [5]. *C. calauanica* has been found to be very specific to *A. rigidus*, although mathematical modeling and simulations by [6] assumed that the parasitoid may exhibit Holling type III functional response in which parasitization on an alternate host is necessary for survival in the absence of the primary host. Predictive geographical modeling that is based on the dependence of species and community distributions on environmental factors has been viewed as an important means to assess the impact of natural and anthropogenic environmental change on the distribution of organisms [7]. Climate-based ecological models can help in conservation efforts by providing information for resource and habitat management [8]. Among the popular algorithms used in modeling species distributions is the maximum entropy (MaxEnt) approach, which requires presence-only data as an indication of the species' occurrence.

Models produced using MaxEnt can be easily understood and interpreted and provide valuable insights on distribution and habitat suitability for a species [9,10]. MaxEnt modeling has been used to predict the current and potential distributions of invasive species [11], as well as those of a variety of forest and agricultural insect pests which include: the large pine weevil, *Hylobius abietis*

*L.*, and the horse-chestnut leaf miner, *Cameraria ohridella* Deschka and Dimič [12], and six tephritid fruit flies [13] in Europe; three species of tephritid flies under genus *Dacus Fabricius* [14] and the European grapevine moth, *Lobesia botrana* Denis & Schiffermüller, in China [15]; the ricaniid planthopper, *Ricania shantungensis* Chou & Lu in Korea [16,17]; and the cotton mealybug, *Phenacoccus solenopsis* Tinsley, in India [18] and worldwide [19]. The use of MaxEnt modeling as a tool in integrated pest management, particularly in forecasting potential areas of new pest invasion relative to climate, has not yet been explored very well in the Philippines. Hence, in view of the use of *C. calauanica* for biological control of *A. rigidus*, the MaxEnt approach was employed in this study to generate a bioclimate-based Species Distribution Model (SDM) for the prediction of either the presence of the parasitoid or suitability of areas for its occurrence. This study provides a peer into the potential of bioclimate-based SDMs as tools for integrated pest management, especially in view of climate change. The ability and utility of the distribution model of a highly specific parasitoid to predict the potential distribution or areas of new invasion by its host are likewise demonstrated.

## Materials and Methods

### Species presence, Bioclimatic variables, and Other data

Presence-only data pertaining to occurrence of *C. calauanica* were derived from GPS coordinates recorded from periodic field surveys conducted from April 2014 to June 2016 in 15 sampling points across three provinces (Batangas, Cavite, and Laguna) in the Southern Tagalog region, and in 4 points in the town of Orani in Bataan in the Central region of Luzon Island Table 1. An additional coordinate was derived using Google Maps (accessible from <http://maps.google.com>) to represent a point in Isabela City, Basilan Island where sightings of *C. calauanica* were reported in January 2016 but was not actually covered by our surveys. The occurrence points were encoded in spreadsheet form (with three columns for species, longitude, and latitude in that order) using Microsoft Excel and saved as a Comma-Separated Values (CSV) file. Bioclimatic data sets were downloaded from the WorldClim Global Climate Database (accessible from <http://worldclim.org/current>). These bioclimatic data were derived from global climate data interpolated by [20] and represent current conditions. The downloaded raster data sets, in BIL format with 30 arc-seconds resolution, pertain to 19 variables Table 2. For visualization of the SDM and subsequent map construction, vector layers (in SHP format) of the administrative boundaries of the Philippines were directly downloaded from the Philippine GIS Data Clearinghouse (accessible from <http://www.philgis.org>).

**Table 1:** Points with confirmed occurrence of *Comperiella calauanica* from April 2014 to January 2016.

Point	Coordinate (WGS 84)	
	Longitude (°)	Latitude (°)
Batangas, Luzon		
Malvar	121.1466	14.04903
Talisay	121.0107	14.09334
Tanauan	121.0913	14.09887
Sto. Tomas	121.2198	14.05746
Cavite, Luzon		
Silang A	120.9729	14.21884
Silang B	121.0305	14.21385
Tagaytay	121.0002	14.17002
Laguna, Luzon		
Calauan	121.2579	14.09737
Los Baños	121.2595	14.15006
Nagcarlan	121.4137	14.15893
Rizal	121.4109	14.06585
Candelaria	121.4513	13.92844
Alaminos	121.2481	14.06618
San Pablo A	121.2948	14.06757
San Pablo B	121.3333	14.05642
Bataan, Luzon		
Orani A	120.4545	14.76979
Orani B	120.4546	14.76963
Orani C	120.4561	14.77067
Orani D	120.4558	14.77054
Basilan Island, Mindanao		
Isabela City*	121.9947	6.587794

\*Not covered by surveys in the current study.

**Table 2:** Bioclimatic variables used in MaxEnt model development for *Comperiella calauanica* [20].

Bioclimatic variable	Variable code
Annual mean temperature (°Cx10)	bio01
Mean diurnal range (°Cx10)	bio02
Isothermality	bio03
Temperature seasonality	bio04
Maximum temperature of the warmest month (°Cx10)	bio05
Minimum temperature of the coldest month (°Cx10)	bio06
Temperature annual range (°Cx10)	bio07
Mean temperature of the wettest quarter (°Cx10)	bio08
Mean temperature of the driest quarter (°Cx10)	bio09
Mean temperature of warmest quarter (°Cx10)	bio10
Mean temperature of coldest quarter (°Cx10)	bio11
Annual precipitation (mm)	bio12
Precipitation of the wettest month (mm)	bio13
Precipitation of the driest month (mm)	bio14

Precipitation seasonality	bio15
Precipitation of the wettest quarter (mm)	bio16
Precipitation of the driest quarter (mm)	bio17
Precipitation of the warmest quarter (mm)	bio18
Precipitation of the coldest quarter (mm)	bio19

### Species distribution modeling using MaxEnt

Maximum Entropy Species Distribution Modeling (MaxEnt) Version 3.3.3k was used to develop the SDM for *C. calauanica*. The presence-only data encoded in CSV served as the sample, while the downloaded bioclimatic data sets in BIL format were used as the environmental layers for model construction. Among the 20 presence records inputted into the algorithm, 18 were used for model training while 13 were used for model testing. Iterations of the optimization algorithm were set to 5000, and Jackknife test was included in the algorithm to provide a measurement of the importance of each bioclimatic variable in the model. Response curves were also generated for assessment of the variables. Two runs of the same model were done so that the first output was set to express values logistically and the second with values set to raw. The HTML outputs were later viewed through Internet Explorer 11, while the outputs in raster form (in ASC format) were visualized, enhanced, and assessed in combination with other geospatial datasets through Quantum GIS (QGIS) Versions 1.8.0 and 3.6.0.

### Analysis and assessment of the species distribution model

The constructed MaxEnt model was evaluated using the result of the Receiver Operating Characteristic (ROC) analysis, with the obtained values for the area under the ROC curve (AUC) serving as a measure of model performance. AUC values closer to 1.0 indicate better model performance compared to those further from 1.0. The testing AUC is considered as the true indicator of the predictive power of the model [9,10]. The bioclimatic variable with the highest percentage contribution to the construction of the model was likewise noted. To infer which among the bioclimatic variables the species appear to respond most positively (i.e., preferred conditions) and to which they respond most negatively (i.e., conditions to which they appear to be most sensitive to) in terms of their occurrence, the trends shown in the response curves of a model were examined and compared with each other. Variables whose response curves showed a clearly unidirectional upward or downward trend were those with putatively greatest impact on potential distribution.

### Validation of predicted distribution

A field survey for *A. rigidus* surveillance was conducted in Zamboanga City and in Isabela City in Basilan Island in Western Mindanao initially from 2016 to 2018. Subsequent surveys were done in late January to early February 2017 for field release of mass-reared *C. calauanica*, and in April 2017 for monitoring of

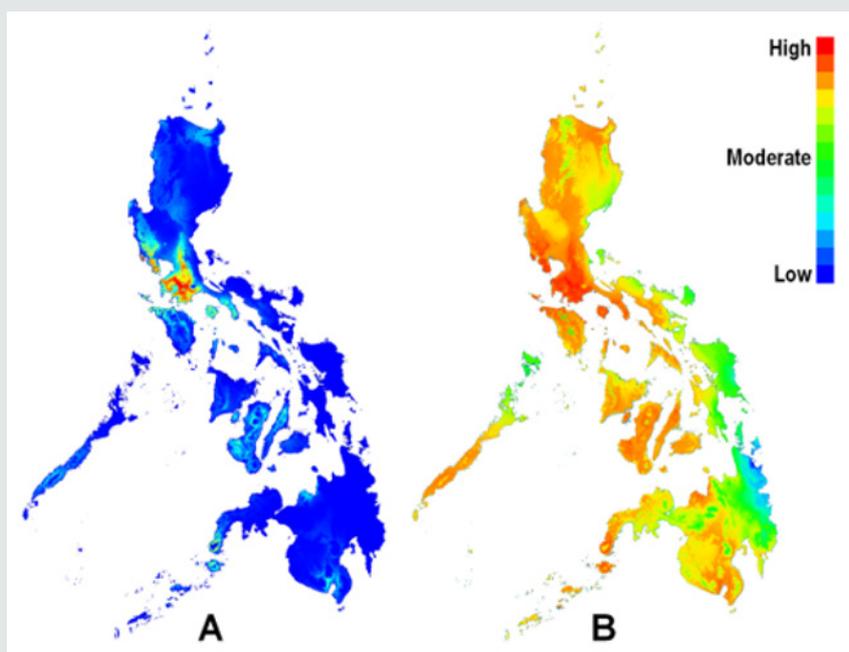
establishment and spread of the parasitoids. Field surveillance was also conducted in Tablas Island in the province of Romblon in January 2018 for confirmation of received verbal reports of *A. rigidus* infestation. GPS coordinates of points where *A. rigidus* infestations were confirmed were recorded and encoded in a CSV file for overlaying of these points on the map with the *C. calauanica* SDM in QGIS. Coincidence of points with areas predicted by the SDM to have non-zero probability (or at least low-moderate suitability) was considered validation of the prediction of occurrence.

## Results and Discussion

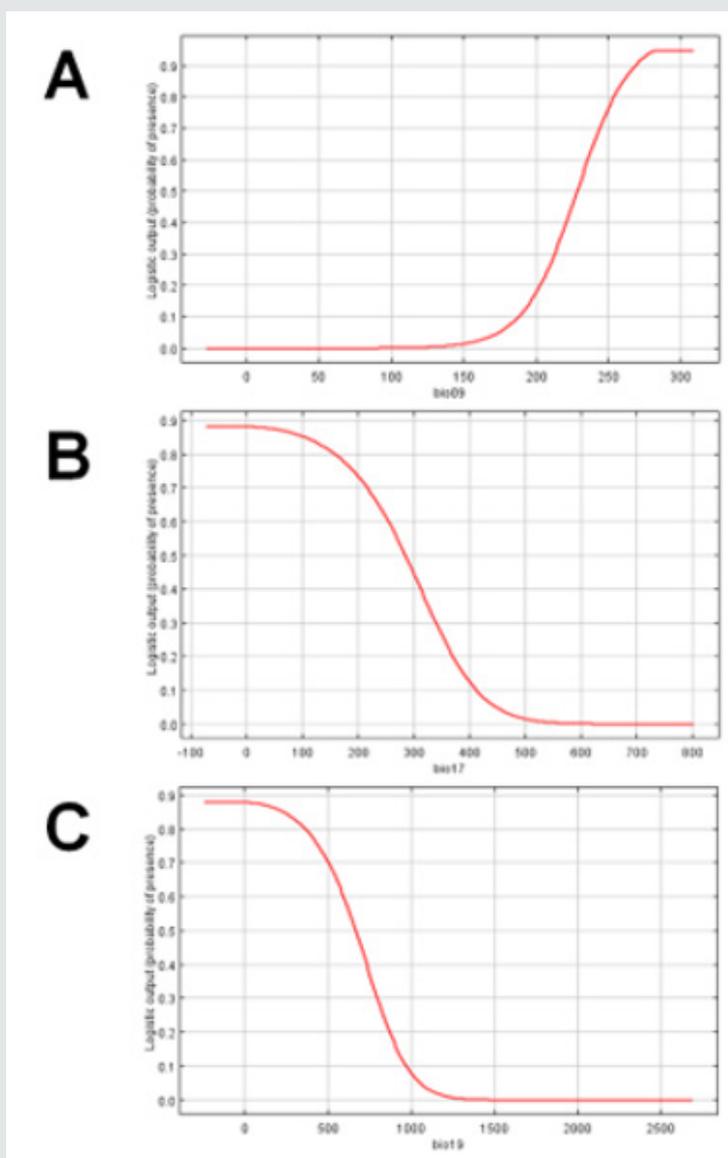
### MaxEnt species distribution model for *Comperiella calauanica*

The generated bioclimate-based distribution model for *C. calauanica* Figure 1 predicts hotspot areas in the provinces of Southern Luzon where the outbreak of *A. rigidus* between 2010 and 2015 most heavily devastated coconut plantations and stands: Batangas, Cavite, and Laguna. It additionally predicts hotspots in the province of Bataan in Central Luzon. These predicted hotspots were expected since all the survey points in the study, and which were inputted into the modeling algorithm, were in those provinces. Areas with non-zero habitat suitability were nonetheless predicted in other parts of the Philippine archipelago that were outside the range of the survey points. Although the model in raw expression Figure 1B shows predictions of moderate to high habitat suitability throughout almost the entire archipelago, areas whose predicted probabilities may be considered substantial (between “low-moderate” and “high”) consistent with the logistic expression Figure 1A include: several other parts of Luzon mainland; other islands in the Luzon island group, notably Mindoro, Palawan,

Marinduque, Romblon, and Masbate; Panay Island; Negros Island; Cebu; Bohol; several parts of Mindanao mainland; Basilan Island; and Sulu. It should be noted that raw values tend to be significantly lower than their logistic equivalent. Given the spectral scale for qualitative interpretation of colors on the SDM, the predicted probability value for a given point could be considered “high” when expressed as raw, but only “moderate” when logistically expressed. This would explain the apparent spectral discrepancy between the raw and logistic expressions of the same SDM. Nevertheless, areas with “low” to “moderate” predicted probability (or habitat suitability) should be treated as potential areas for population establishment, especially if preferable environmental conditions beyond bioclimate (e.g. presence of hosts) may occur in such areas. The SDM was developed for *C. calauanica*, which has been found to be very specific to its diaspidid host, *A. rigidus*. Although recent mathematical modeling with simulations assumed Holling type III functional response [6] which would require *C. calauanica* to parasitize an alternate host in the absence of *A. rigidus*, such alternate host has not been found and the parasitoid is so far known to parasitize only *A. rigidus*. Hence, it is reasonable to view MaxEnt SDM for *C. calauanica* as a predictive model that may also apply to its primary host, especially in view of the confirmed occurrence of *A. rigidus* in all of the 20 points that served as input to the modeling algorithm Figure 1. *A. rigidus* without *C. calauanica* was confirmed in Zamboanga City Figure 2A-B and in Tablas Island Figure 2E-F, whereas *C. calauanica* was confirmed to parasitize *A. rigidus* in Isabela City Figure 2C-D. The infestation in Zamboanga City at the time of the initial surveillance was not yet at the outbreak level, whereas an outbreak appeared to have already started in Tablas Island by the time surveillance under this study was carried out.



**Figure 1:** Bioclimate-based SDM for *Comperiella calauanica* in logistic (A) and raw (B) expressions of calculated probabilities. Warmth of color indicates relative probability of occurrence or suitability of habitat.



**Figure 2:** Response (probability of presence) of *Comperiella calauanica* to selected bioclimatic variables: (A) mean temperature of the driest quarter; (B) precipitation of the driest quarter; and (C) precipitation of the coldest quarter.

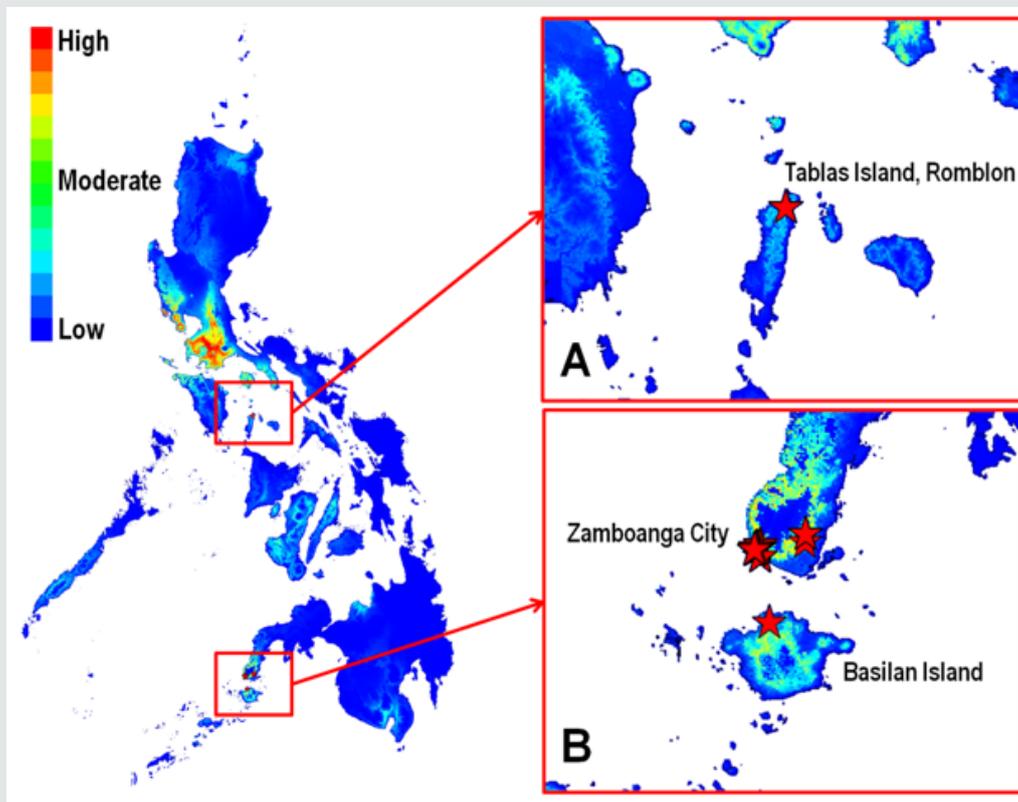
### Model Performance and Contribution of Bioclimatic Variables

The training AUC value of the *C. calauanica* SDM was 0.996, and the test AUC value was 0.966 (standard deviation=0.005). Both values are higher than 0.8, the value above which the AUC must be for the predictive ability of the model to be considered “convincing” [21]. The *C. calauanica* SDM, therefore, has very high predictive power based on these AUC values. Precipitation seasonality (bio15) was the variable found to have the highest relative contribution in the development of the model at 51.5%. This suggests that distribution of *C. calauanica* may be influenced more by precipitation than by temperature, especially considering that the Philippines is a tropical country, where temperatures throughout the year tend to vary less than in temperate regions. In comparison, variables

pertaining to temperature or its variations were found to have significant influence on the predicted distributions of insect pest species in temperate regions, namely *Dacus spp.* [14] and *Lobesia botrana* [15] in China, *Ricania shantungensis* in Korea [17], *Hylobius abietis* and *Cameraria ohridella* in Europe [12], and six species of tephritid fruit flies in Europe [13]. Three bioclimatic variables were found to have clear unidirectional upward or downward trends, and therefore potentially having the greatest impact on occurrence Figure 3. Response curves for these variables indicate that the probability of occurrence of *C. calauanica* increases with higher mean temperatures of the driest quarter and decreasing with higher precipitation during the driest and during the coldest quarters of the year. These findings suggest that the parasitoid could be sensitive to precipitation and may find habitats with higher mean temperatures and relatively less precipitation to be more suitable.

Furthermore, it could be noted in the set of response curves that the predicted probability of occurrence remained constant across changes in variables pertaining to temperature more than precipitation, namely annual mean temperature (bio01), maximum temperature of the warmest month (bio05), minimum temperature

of the coldest month (bio06), and mean temperature of the warmest quarter (bio10). If these response curves provide an approximation of the actual ecophysiological responses of *C. calauanica*, then it is possible that habitat suitability for either insect may be influenced more by precipitation than by temperature.

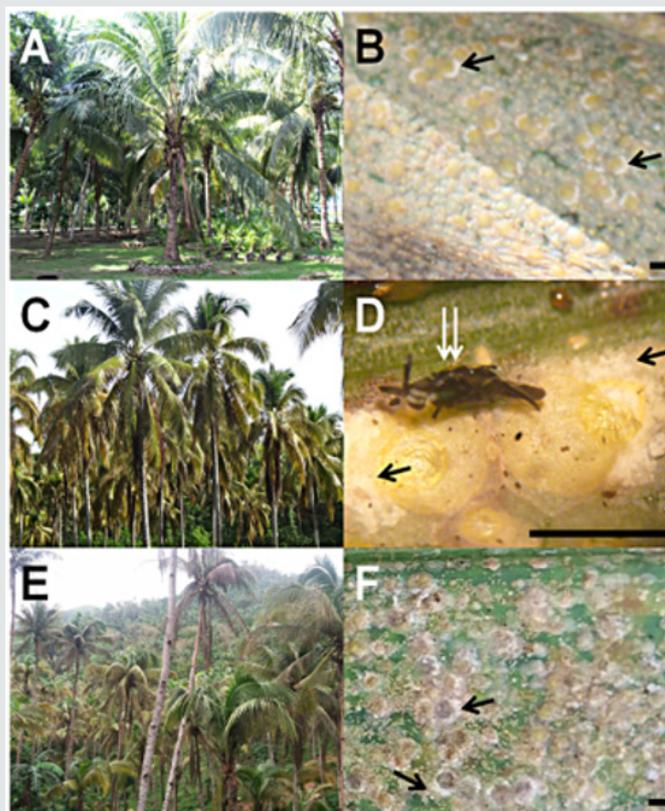


**Figure 3:** MaxEnt SDM of *Comperiella calauanica*, with areas in Romblon (A) and Western Mindanao (B) where infestations of *Aspidiotus rigidus* had been confirmed. Red stars mark the points where confirmatory surveys were conducted between November 2016 and January 2017.

### Confirmation of Occurrences Predicted by the MaxEnt Model

The MaxEnt SDM predicted moderate to high habitat suitability in areas outside the previously known and reported *A. rigidus*-infested areas in Luzon (Southern Tagalog region and Orani, Bataan) and in Basilan Island in Mindanao. These areas include Zamboanga City and Romblon. Field surveillance confirmed the occurrence of *A. rigidus* in Zamboanga City, in Isabela City in Basilan Island, and in Tablas Island, Romblon Figure 4. Presence points used in development of the *C. calauanica* SDM were limited only to the known outbreak and infestation areas from 2014 to early 2016, and were limited to only 20 points, including one that was derived from Google Maps. Findings from field surveys conducted in late 2016 up to 2018 validated these predictions, consistent with the high

predictive power of the SDM as indicated by the high training and test AUC values computed by MaxEnt. Previously reported MaxEnt models for other insect species were developed using between twice to more than thirty times as many occurrence records Table 3. Nevertheless, the SDM developed for *C. calauanica* using relatively few points was able to correctly predict the occurrence of *A. rigidus* in Zamboanga City and in Romblon, and together with the parasitoid in Basilan Island. MaxEnt has been recognized for being much less sensitive to sample size compared to other distribution modeling algorithms, capable of being able to produce useful, predictive models with as small as 5 occurrence points [22,23]. To date and to our knowledge, this is the first field-based validation of the occurrence or habitat suitability predicted by MaxEnt SDM for an insect species that is important to agriculture or forestry.



**Figure 4:** *Aspidiotus rigidus*-infested coconut trees with magnified view of scale colony samples from: Zamboanga City (A and B); Isabela City, Basilan (C and D); and Tablas Island, Romblon (E and F). Black arrows point to the characteristic distribution of eggs and egg skins along the pygidial ends of mature female *A. rigidus* which can be used as basis to quickly distinguish this species from other *Aspidiotus spp.* on coconut. White double arrow points to female *Comperiella calauanica*. Scale bars on the photomicrographs approximate 1.0mm.

**Table 3:** Number of occurrence points used for MaxEnt modeling of selected insect species with respective test AUC values.

Species	Number of occurrence points used in MaxEnt modeling	Test AUC	Reference
Anastrepha fraterculus	49	0.76*	Godefroid et al. (2015)
A. obliqua	49	0.77*	Godefroid et al. (2015)
Bactrocera cucurbitae	49	0.91*	Godefroid et al. (2015)
B. oleae	49	0.97*	Godefroid et al. (2015)
Cameraria ohridella	152	0.97	Barredo et al. (2015)
Ceratitis fasciventris	49	0.82*	Godefroid et al. (2015)
Comperiella calauanica	20	0.966	Current study
Hylobius abietis	677	0.93	Barredo et al. (2015)
Lobesia botrana	95	0.970*	Lv et al. (2012)
Phenacoccus solenopsis	111	0.895	Fand et al. (2014)
P. solenopsis	201	0.92	Wei et al. (2017)
Ricania shantungensis	43	0.79	Baek et al. (2019)

\*Not indicated if AUC value refers to test AUC or training AUC.

### Conclusion

MaxEnt was used to develop a bioclimate-based SDM for *C. calauanica*, the highly specific endoparasitoid of the destructive coconut scale, *A. rigidus*, in the Philippines. The SDM predicted

moderate to high habitat suitability in areas in Luzon Island as well as in other parts of the archipelago. Some of the hotspots were predicted in areas that were not covered by field surveillance in 2014 to 2016, through which the limited number of occurrence points used in model development were obtained. Despite the

relatively small sample size used for model development, the SDM was determined to have an excellent predictive power as indicated by the very high training and test AUC values computed by MaxEnt. Field surveys conducted in late 2016 to early 2017 confirmed the occurrence of *A. rigidus* in Zamboanga City, as well as in Isabela City in Basilan Island in Western Mindanao, where the SDM predicted hotspot areas. Subsequently, *A. rigidus* was also confirmed through field surveillance in Tablas Island in Romblon, where moderate to high habitat suitability was also predicted. These findings point to the utility of the *C. calauanica* SDM in predicting habitat suitability or probability of occurrence of the coconut pest which caused a devastating outbreak in the Southern Tagalog region of Luzon Island from 2010 to 2015. This study has demonstrated how bioclimate-based modeling may have considerable potential as a tool for pest invasion forecasting and surveillance. Modeling based not only on current conditions but also on projected future conditions should be considered and further assessed. MaxEnt modeling was also able to provide insights into possible responses of *C. calauanica* or *A. rigidus* to climatic factors, particularly precipitation. We recommend that controlled assessments be done to determine the ecophysiological responses of either *C. calauanica* or *A. rigidus* to such climatic factors and verify the MaxEnt-predicted responses. Sufficient understanding of the ecophysiology of insects, supplemented by valuable information that can be provided by bioclimate-based SDMs, may help in the development of pest invasion risk maps, not only for *A. rigidus* but also for other species of importance to agriculture or forestry in the Philippines, especially in view of climate change.

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## Conflict of Interest

The authors declare no conflict of interest.

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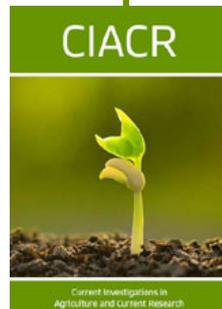
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