Preliminary Species Distribution Modelling for Florida Wax Scale, *Ceroplastes floridensis* Comstock in Mindanao Island, Philippines

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Abstract

An invasion of Ceroplastes floridensis Comstock, Florida wax scale (FWS), which is not known to occur in the Philippines but was recently found infesting mangoes in Davao del Sur, is under strict pest surveillance. This study aims to determine the potential distribution of FWS in mainland Mindanao using environmental, topographic, and ecological factors under different climate scenarios: historical, RCP 4.5, and RCP 8.5 at moderate emissions. Concerning infestation foci, FWS distribution was predicted to spread south-westerly based on the constructed SDMs (AUC = 0.988–0.995) across climate projections. Average annual temperature, elevation, and the presence of seedling sources were identified as the most influential factors. This study emphasizes the importance of containment measures for FWS from infestation foci (i.e., infested mango farms) and other potential sources of infested plant propagules to prevent further spread to other mango-growing areas in Mindanao and the rest of the archipelago.

Keywords: biological invasion, mango pest, incursion risk, scale insect, species distribution model

1. Introduction

Biological invasions pose significant risks to the economy, ecology, and biodiversity, both locally and globally (Department of Environment and Natural Resources-Biodiversity Management Bureau [DENR-BMB], 2016; Zenni *et al*., 2021; Huron *et al*., 2022; Lenzner *et al*., 2024). These invasions follow five phases: introduction, establishment, lag phase, dispersal, and outbreak (Wan and Yang, 2016). The rapid pace of trade and globalization facilitates the movement of invasive species into new areas (Bellard *et al*., 2016; Venette and Hutchison, 2021). In agriculture, invasive pests exploit resources provided by cultivated crops, enabling their establishment and spread (Guillemaud *et al*., 2011). Among the most pervasive challenges are invasive insects, which threaten global development and prosperity by compromising food security, water resources, resilient environments, and economies (Venette and Hutchison, 2021).

The Florida wax scale insect (FWS), *Ceroplastes floridensis* Comstock, 1881 (Hemiptera: Coccoidea: Coccidae), was recently found infesting mango farms in Davao del Sur, posing a significant threat to mango production in the Philippines. Abiotic factors such as temperature and relative humidity heavily influence the abundance and distribution of scale insect species like FWS (Camacho and Chong, 2015). Adult FWS, measuring 2 to 4 mm in length and 1 to 3.5 mm in width, are elliptical, reddish-brown, and have short anal processes (Hamon and Williams, 1984). FWS nymphs damage their hosts by sucking plant fluids, causing leaf discoloration, premature leaf drop, branch dieback, and even plant death (Sharma and Buss, 2011). In mangoes, FWS also induces sooty mold formation, which damages fruit and hinders photosynthesis (Swirski *et al*., 1997).

Florida wax scale insect (FWS), *Ceroplastes floridensis* Comstock, 1881 (Hemiptera: Cocoidea: Coccidae), was recently found infesting mango farms for the first time in Davao del Sur and poses a threat to mango production in the country for case its population escalates with further spread. The abundance and range of scale insect species like FWS can be largely influenced by abiotic factors such as temperature and relative humidity (Koztarab, 1996 in Camacho and Chong, 2015). Adults of FWS range from 2 to 4 mm in length and 1 to 3.5 mm in width (Sharma and Buss, 2011) and are elliptical, reddish brown, and with short anal processes (Hamon and Williams, 1984). Three nymphal instars (Drees *et al*., 2006) develop from eggs laid under the adult female scale's wax covering (Sharma and Buss, 2011). Native in the U.S., FWS is known to have three generations per year (Johnson and Lyon, 1991), but commonly, two generations are observed throughout its known global range, including Asia. FWS nymphs directly damage their host by sucking large amounts of plant fluids; high infestation level causes leaf discoloration, premature leaf drop, branch dieback, and possibly plant death (Sharma and Buss, 2011). In mangoes, it also causes sooty mold, which culls the fruit and affects the physiological processes of trees, such as photosynthesis (Swirski *et al*., 1997).

Trade and domestic transport facilitate dispersal for scale insects despite their limited mobility. This dispersal mechanism is evident in FWS, which has expanded from temperate regions like the United States to a global distribution, including Southeast Asia (European and Mediterranean Plant Protection Organization [EPPO] Global Database, 2023; Centre for Agriculture and Biosciences International [CABI], 2023). In the Philippines, five Ceroplastes species are known to occur; however, FWS has not been previously documented infesting mangoes (I. Lit Jr., personal communication, 2021). A recent infestation of FWS was reported in mango farms in Matanao and Magsaysay, Davao del Sur. This study examines its potential spread and establishment in other mango-growing regions of Mindanao.

In the Philippines, there are five species of Ceroplastes known to occur, *viz. Ceroplastes stellifer* (Westwood, 1871), *C. rubens* (Maskell, 1893), *C. ceriferus* (Fabricius, 1798), *C. cirripediformis* (Comstock, 1881), and *C. sinensis* (Del Guercio, 1900) (EPPO Global Database, 2023, CABI, 2023), the Florida wax scale is not one especially infesting mangoes (I. Lit Jr., personal communication, 2021). However, a recent infestation of the said non-native scale insect species was observed in mango farms in the municipalities of Matanao and Magsaysay in Davao del Sur, Mindanao. As an alien species, initial assessments indicate potential damage to mango trees, its potential to spread, and establish locally in areas where this economically important fruit crop is cultivated urgently needs to be examined.

Species distribution models (SDMs) are becoming a popular tool for predicting habitat suitability, distribution, and future outbreak foci of major insect pests that affect crop productivity (Qin *et al*., 2015; Prabhulinga *et al*., 2017; Yeh *et al*., 2021; Pangga *et al*., 2021). In general, SDM relates recorded species presences or occurrences to environmental variables that are thought to determine the species' distribution (Araujo and Peterson, 2012 in van Proosdij *et al*., 2016). SDMs are useful in modeling a species distribution under climate change scenarios (Ahmad *et al.*, 2019). With these, species' climate space can be determined, and a clear delineation of its climatic niches can be provided (Ranjitkar *et al.*, 2014). In this study, the maximum entropy (MaxEnt) modeling approach was used to predict the risk of invasion of FWS due to environmental predictors and an inferred model of dispersal.

2. Methodology

2.1 Insect Pest of Concern

The initial taxonomic identification of field-collected wax scales was done at the Insect Ecology Laboratory, UP Los Baños. It was taxonomically verified by Dr. G.W. Watson of the Natural History Museum, London, and confirmed with molecular identification (DA-BPI, personal communication). It was first found infesting mango trees in Davao del Sur, Philippines (Figure 1). The country's FWS introduction point was identified in Bacungan, Magsaysay, Davao del Sur. A total of 25 mango farms, where infestations of the said scale insect pest were found, were geotagged using a Global Positioning System (GPS) device.

2.2 Presence-only Data

Presence-only data were collected from surveys in collaboration with the Department of Agriculture-Regional Field Office XI. Coordinates were converted to decimal degrees and encoded in a spreadsheet for SDM modeling. Occurrence records were aggregated to match the spatial resolution of environmental predictors (Table 1).

Table 1. Main parameters used in modeling the distribution of Florida wax scale in mainland Mindanao

Variable	Code	Unit	Source	Purpose
Average Annual Rainfall	AAR	mm	DOST-PAG-ASA-IAAS-CAD	Climate
Average Annual Temperature	AAT	ºC	DOST-PAG-ASA-IAAS-CAD	Climate
Elevation	E	m	US - NASA, NGA	Topographic
Slope	S	degree (º)	Derived from E	Topographic
Seedling Source (Dispersal)	D	N	DA-BPI- Region XI	Ecological
Land use	LU	n/a	NAMRIA	Ecological

N = Total number of commercial mango seedling nurseries (potential source of infested plants/plant parts).

2.3 SDM Predictors

NASA's Shuttle Radar Topography Mission digital terrain model (DEM) (NASA SRTM, v3.0, 2013) with a spatial resolution of three arcsecs (~ 90 × 90 m) served as the elevation raster data, from which the slope was subsequently derived. The climatic predictors used were dynamically downscaled seasonal climate projections for annual precipitation and temperature climatic variables acquired from the Philippine Atmospheric, Geophysical and Astronomical Services Administration Impact Assessment and Applications Section - Climatology and Agrometeorology Division (PAGASA-IAAS-CAD). These include the baseline climate projection from 1971 to 2000 and future climate projections from 2046-2065 for two scenarios, namely Representative Concentration Pathways (RCP) 4.5 and 8.5, both at moderate emission levels (Department of Science and Technology [DOST]-PAGASA, 2021). These numerical projections for climate data were vectorized and rasterized subsequently. A land use map was obtained from the National Mapping Resource Information Authority (NAMRIA) database, rasterized, and reclassified using 'reclassify by table'. A list of accredited mango seedling nurseries was sourced from the Bureau of Plant Industry – Region XI and supplemented by Google Map searches to determine the geographical coordinates of each nursery in mainland Mindanao, after which, counted at the provincial level, vectorized, rasterized, and reclassified accordingly. All data vectorization, rasterization, and reclassification except for elevation were made in QGIS (v.3.20.3, 2021). Raster resolution alignment was done via the 'resample' function with 'WGS84' as the default coordinate reference. Using the aligned raster data, different raster stacks were created using the 'stack' function based on each set or group of predictors (I, II, and III) (Table 2). All raster alignment and stacking were done using the 'raster v.3.6-30' package (Hijmans, 2024a) in R v. 4.1.1.

Table 2. Set of predictors used in SDM models

Set/Grouping	Description
I	All Predictors
II	AAT+AAR+ E+S
III	AAT+AAR+LU+D

2.4 Species Distribution Modelling

SDMs were fitted using the ‘maxent’ function with settings (regularization values: 0.500, categorical: 0.250, threshold: 1.830, hinge: 0.500, feature type: hinge linear quadratic) in the ‘dismo v.1.3.16’ package (Hijmans *et al*., 2024). FWS occurrence data were partitioned into training data (80% of occurrence points) and test data (20% of occurrence points) (*kfold*=5) (Phillips *et al*., 2004; Phillips *et al*., 2006; Elith *et al*., 2011). Selected model performance metrics such as Receiving Operator Characteristic (ROC) computing for Area Under Curve (AUC), Cohen’s kappa-statistic (*k*), and sensitivity were obtained for each SDM. Afterwards, a ‘SpatRaster’ (SWD object) was created for each set of predictors via the ‘terra v.1.8-15’ package (Hijmans, 2024b). Each was used as input to evaluate the relative importance of each model through jackknife tests via the ‘SDMtune v.1.3-2’ package (Vignali *et al*., 2022). All SDM procedures were performed using the aforementioned packages in R v.4.1.1.

3. Results and Discussion

3.1 Potential FWS distribution in Mainland Mindanao

Using the 25 recorded presence points (Figure 1), environmental covariates, and sources of infested seedlings (inferred dispersal potential) (Figure 2), the FWS distribution model was created at baseline and two future climate change scenarios *viz.* RCP 4.5 and RCP 8.5. As shown in Figure 3, considering all parameters, land use (*LU*) consistently had the highest percent contribution (i.e., importance) to the modeled FWS distribution (25.39% - 29.63%) both for baseline and for future climate scenarios. On the other hand, when only set II predictors were considered, elevation contributed the most to the modeled FWS distribution (30.19% - 40.59%) in all climate scenarios. When only climatic, seedling source and land use were used to model FWS distribution, LU contributed significantly to baseline and RCP 4.5 climate scenarios, 30.04 % and 29.10%, respectively. Meanwhile, the number of seedling sources (*D*) was the second highest contributing parameter at baseline and RCP 4.5 climate scenarios, except for models where Set II predictors were only used. AAT was observed to contribute the highest at RCP 8.5 climate scenarios (Figures 3- c, f, and i), ranging from 29.62% to 30.09%, whereas AAR largely influenced the predicted FWS distribution at baseline and RCP 4.5 climate scenarios (Figures 3- d, e, g, and h) from 20.58% - 23.43%.

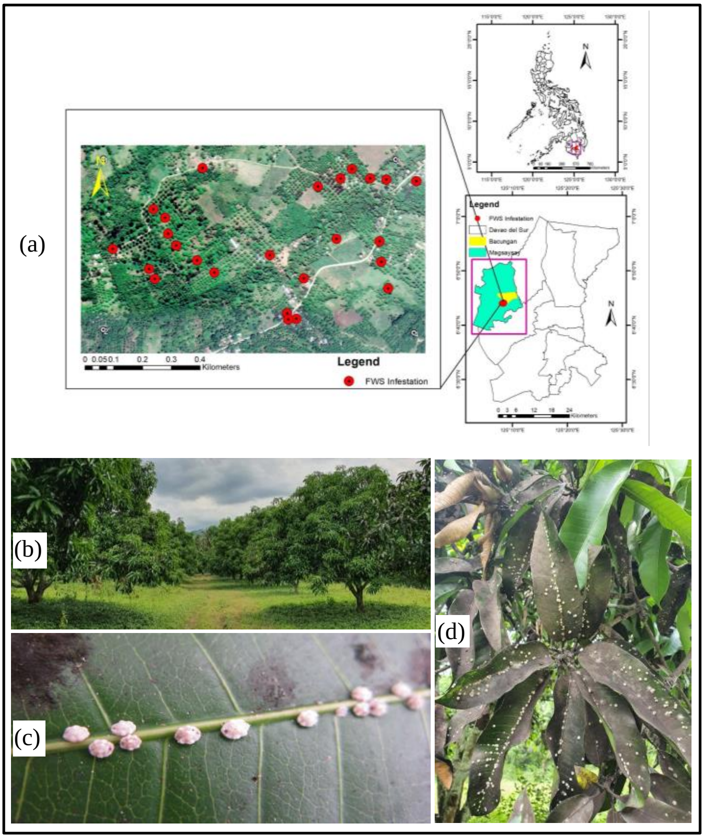

Figure 1. FWS found on mango trees in Davao del Sur: location of infested mango trees (a); FWS - infested mango trees (b); FWS adults on a mango leaf (c); FWS on mango tree foliage with sooty molds' damage (black coloration on leaves) (d)

Aside from permutation importance, jackknife tests were also performed to determine variable importance for each model using different predictors at three climate scenarios. For models created using set I predictors, the slope was the least important predictor for FWS distribution, whereas E and D were the most important predictors in all climatic scenarios (Figures 4a-c). On the other hand, for models where set II predictors were used, the slope was the least important predictor except for the RCP 8.5 model (AAT). E and AAR were the most important predictors in all climatic scenarios (Figures 4d-f). For models that utilized set III predictors, AAT is the predictor with the least importance, whereas LU and dispersal have the greatest importance as predictors (Figures 4 g-i).

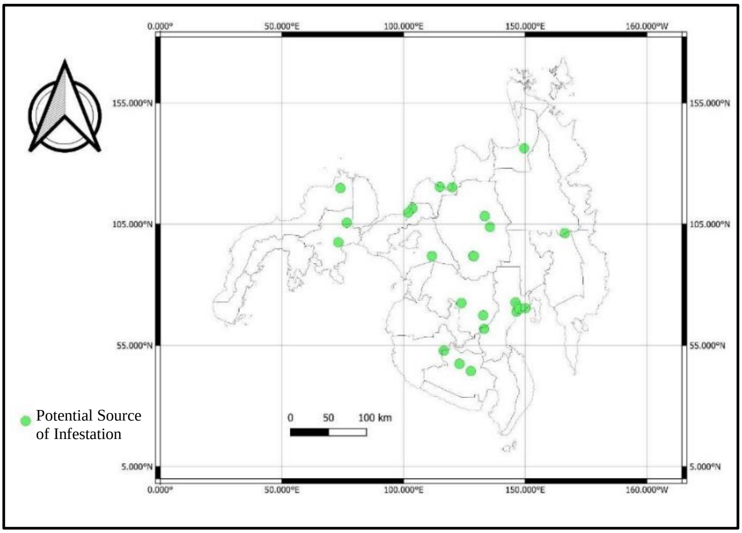

Figure 2. The location of mango seedling nurseries in mainland Mindanao was used as a proxy to quantify FWS dispersal potential.

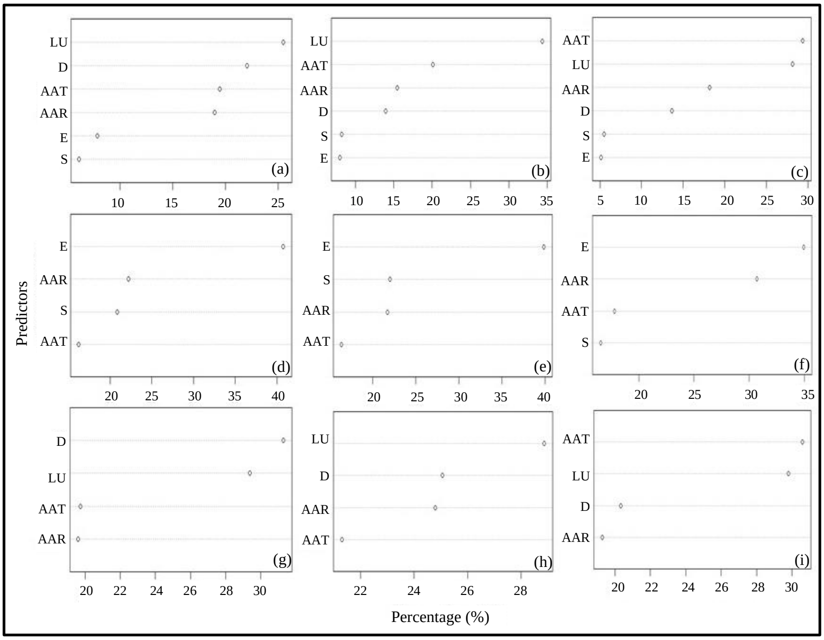

Figure 3. Permutation importance of parameters used for the FWS distribution models in mainland Mindanao. SDM using set I predictors (a-c), set II (d-f), set III (g-i) at different climate scenarios: baseline (a, d, g), RCP 4.5 (b, e, h), and RCP 8.5. (c, f, i); the open circle indicates percentage value.

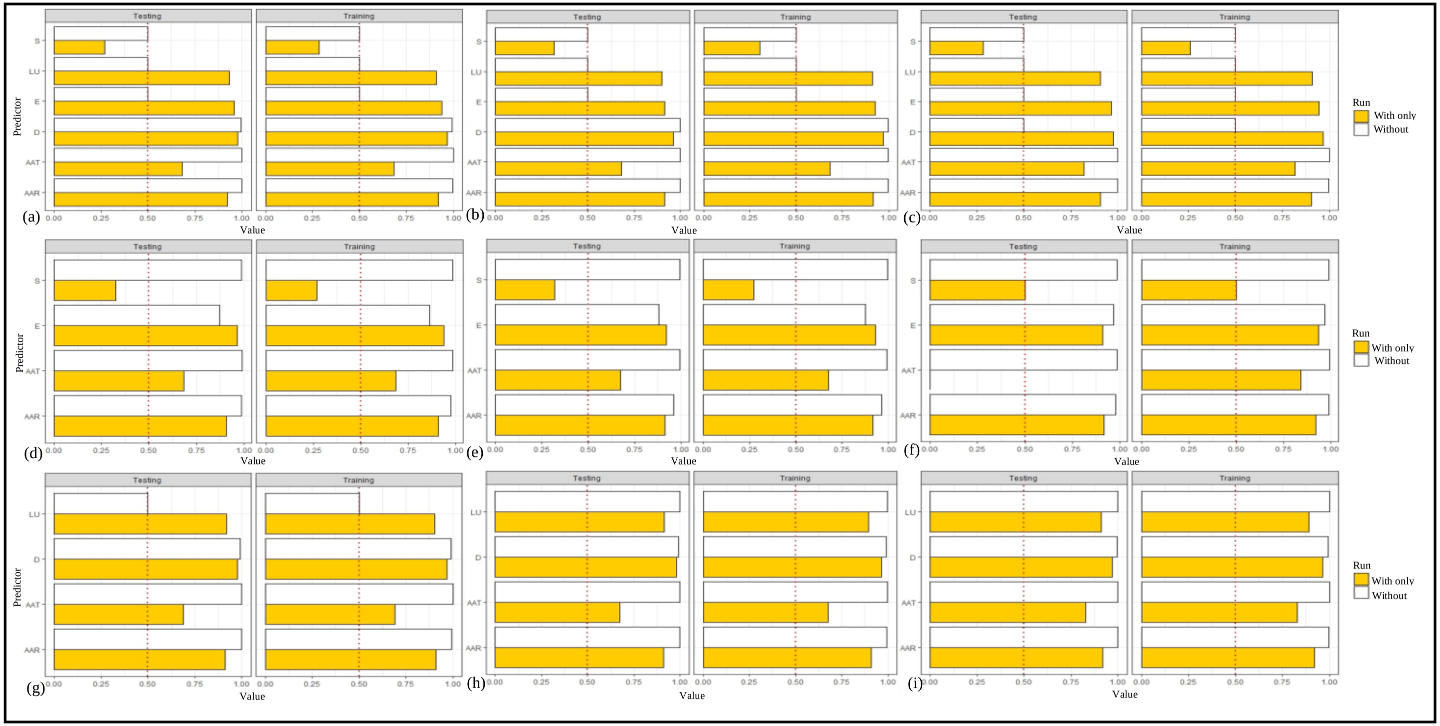

Figure 4. Jackknife test results. Jackknife plot for baseline (a), RCP 4.5 (b), and RCP 8.5 (c) using set I predictors; Jackknife plot for baseline (d), RCP 4.5 (e) and RCP 8.5 (f)) using set II predictors; Jackknife plot for baseline (g) and RCP 4.5 (h) and RCP 8.5 (i) using set III predictors

In general, from the infestation foci in Magsaysay, Davao del Sur, FWS distribution in mainland Mindanao was predicted to spread in the southernmost provinces (Figure 5). Also, concerning the foci, a westerly spread was shown in models using baseline, RCP 4.5, and RCP 8.5 climate scenarios. More specifically, with all predictors considered, at baseline scenario, suitable conditions for FWS establishment were found at the northern portion of Davao del Sur and with moderate to low suitable conditions westerly from infestation foci, which include some areas of South Cotabato, North Cotabato, Maguindanao and Sultan Kudarat (Figure 5a). In the RCP 4.5 scenario, using the same set of predictors, FWS distribution was predicted to be higher also in Davao del Sur but lesser in Cotabato provinces and also in some parts of Davao del Norte (Figure 5b). With the same features, at RCP 8.5, FWS distribution was confined between northern parts of Davao del Sur and South Cotabato (Figure 5c).

With set II predictors used, areas for FWS establishment ranging from low to high suitability were shown to increase in the provinces of Davao del Sur, South Cotabato, North Cotabato, Maguindanao, and Sultan Kudarat in both baseline and RCP 4.5 scenarios (Figures 5 d and e, respectively). On the other hand, this was not the case in the RCP 8.5 scenario, where FWS distribution was not well predicted in Davao del Sur, South Cotabato, and North Cotabato (Figure 5f). Meanwhile, using climate, land use, and potential seedling source, the predicted distribution of FWS was shown to be high in selected northern parts of Davao del Sur, with low suitability in some parts of North and South Cotabato provinces at baseline (Figure 5g) and RCP 4.5 (Figure 5h) scenarios. AT RCP 8.5 climate scenario, low to high predicted distribution was found only in Davao del Sur and South Cotabato (Figure 5i).

Measures of model accuracy were obtained based on the models from the different sets of predictors at three climate scenarios (Table 3). With respect to the three sets of predictors used, the computed AUC values differ across each climatic scenario. The distribution model at the baseline scenario consistently had the lowest AUC value generated (0.987-0.990). On the other hand, the highest AUC values were recorded for RCP 8.5 distribution models (0.994-0.995). All models, regardless of climate scenario, yielded AUC values> 0.7. Another measure of accuracy presented is Cohen’s kappa, where the highest values were calculated at the baseline scenario (0.831 and 0.864) except when modeled using set III predictors. Across models, the highest *k* was obtained from the model built from set II predictors at baseline conditions (0.864). In contrast, the lowest was for the model at baseline scenario using set III predictors. Regarding sensitivity, the highest value was recorded for the RCP 8.5 model using Set III predictors at 0.912 and the least for the RCP 4.5 model created utilizing Set II predictors at 0.002.

3.2 Discussion

Using different predictors, FWS potential distribution in mainland Mindanao was determined at three climate scenarios. A south-westerly spread is predicted for this non-native scale insect pest in areas of Mindanao where local fruit crop farms are present with available host plants or alternate host plants, particularly mango. FWS has been reported beyond its native range in Southeast Asian countries such as Indonesia, Malaysia, and Vietnam (EPPO Global Database, 2024), where host plants were reportedly infested, given favorable climate and environmental conditions. Climatic factors, such as AAR, contributed most significantly to its potential distribution at baseline, RCP 4.5, and RCP 8.5 climatic scenarios using Set II predictors. Moreover, AAT contributed slightly to its distribution when Set I and II predictors were used. These results align for a congeneric species, the barnacle scale *Ceroplastes cirripediformis,* wherein temperature-derived bioclimatic variables such as the mean temperature of the driest quarter, precipitation of the coldest quarter, precipitation of the warmest quarter, and mean temperature of the wettest quarter were found to be the main factors influencing its current and future distribution models using Maximum Entropy algorithm (Wang *et al*., 2021).

Similarly, another congeneric species, the fig wax scale, *Ceroplastes rusci*, current distribution was highly attributed to temperature annual range and mean temperature of the warmest quarter. At the same time, its potential range expansions or reductions were also predicted under different future climate change scenarios using the same algorithm (Shan *et al*., 2023). The MaxEnt distribution model at both baseline and future climate scenarios for *Ceropslastes spp.* in these studies was done at a larger scale (i.e., continental scale), which also used a larger number of presence records (*N >100*). In contrast, the current study attempted to model *C. floridensis* at a smaller spatial scale (i.e. island) with fewer records (*N=25*). The lower limit depends on the species' prevalence for a minimum number of occurrence localities, with absolute minimum sample sizes as low as 3 for narrow-ranged and 13 for widespread species (van Proosdij *et al*., 2015). Meanwhile, generally speaking, for scale insects, present findings also parallel for a diaspidid scale insect, *Aspidiotus rigidus*, wherein rainfall was found to be more important than temperature in the MaxEnt distribution models (Pangga *et al*., 2021).

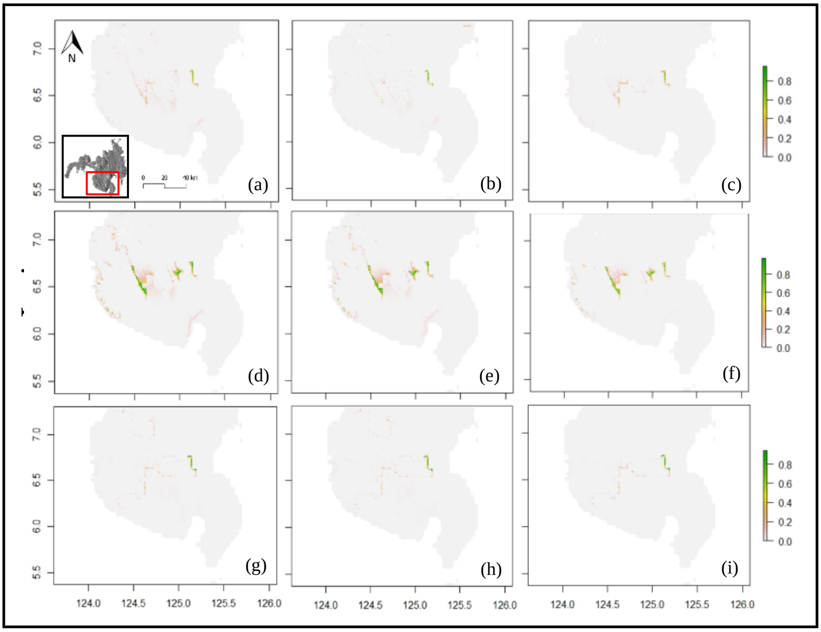

Figure 5. Maxent models constructed for FWS at different scenarios: baseline-all predictors (a), RCP4.5 - all predictors (b), RCP 8.5-all predictors (c), baseline-AAT+AAR E+S (d), RCP4.5 - AAT+AAR+ E+S (e), RCP 8.5 – AAT+AAR E+S (f), baseline-AAT+AAR+LU+D (g); RCP 4.5-AAT+AAR+LU+D (h), RCP 8.5-AAT+AAR+LU+D (i); suitability scale: 1 as highly suitable (shown in green)

In addition, in the current study, reclassified land use (*LU*) assumed herein to indicate host plant availability (i.e. areas planted with fruit tree crops) was found to highly contribute to the predicted FWS distribution in all climate scenarios using Set III predictors. Inclusion of land use apart from climatic factors in modelling distribution of scale insects is essential given that host plant availability is indispensable for introduced scale insects to survive, reproduce and finally spread. In a recent review it was emphasized that insect invasion rates continue to accelerate not only due global trade, climate change but also to land use modification (Abram *et al*., 2024). Moreover, early on it was suggested that in examining the relationship between landscape and insect populations, the influence of regional land use cannot be disregarded (O’Rourke *et al*., 2011).

Another predictor found to potentially influence FWS distribution in Mindanao using Set I predictors at baseline and future climate scenario was the presence of seedling sources where FWS dispersal potential (*D*) was inferred. Commercial trade of tree seedlings including for fruit crops is an economic activity in Mindanao (Mercado and Piñon, 2008) especially that accredited nurseries which supply certified grafted mango seedlings are present and it is viewed here that this could be a potential mechanism for regional and countrywide spread of FWS. For scale insects, newly emerged nymphs are dispersed up to several kilometers, mainly by the wind (Hanks and Denno, 1993); however, dispersal through the transfer of infested plant materials through trade, harvest, or commodities is widely documented both regionally and globally (Dale *et al*., 2020; Fenn-Moltu *et al*., 2022). It was recently posited that globally, propagule pressure whereby movement of infested planting materials as a potential mechanism, is one main driver of high invasion success rate for non-native hemipteran species (Liebhold *et al*., 2024).

3.3 Model Limitations

The main contribution of this study is to raise awareness of the potential spread of FWS, a non-native scale insect in the country with the aid of presented SDMs but these certainly have limitations. For instance, the predicted FWS distribution was largely dependent on the data inputs and specific settings, wherein only defaults were used such for regularization of the modelling algorithm. Also, pre-modelling steps such as multicollinearity tests were not done for the different predictors or variables used in the SDMs. In addition, given the spatial scale considered in this study, spatial bias correction was not applied for the models constructed. Species distributions that are generated from a specific model may deviate from actual distributions and are therefore prone to bias (Qian *et al*., 2020). In this sense, further improvements in SDM model generation for FWS is warranted for more accurate approximations and to address issues on over-fitting for better use in policy-making, planning and management for this new incursion of scale insect pest in the country.

Table 3. Model performance and evaluation metrics for the SDMs constructed for FWS

Set	SDM model	AUC	*k*	Sensitivity
I. All Predictors	Baseline	0.990	0.831	0.896
	RCP4.5	0.988	0.736	0.002
	RCP 8.5	0.995	0.756	0.823
II. AAT+AAR+ E+S	Baseline	0.990	0.864	0.781
	RCP4.5	0.991	0.805	0.845
	RCP 8.5	0.994	0.682	0.721
III.AAT+AAR+LU+D	Baseline	0.987	0.461	0.564
	RCP4.5	0.988	0.689	0.829
	RCP 8.5	0.995	0.830	0.912

**Each value was shown in three decimal places to show slight changes.*

4. Conclusion and Recommendation

SDMs generated for FWS in mainland Mindanao show that this newly introduced insect pest can potentially spread and establish locally and that temperature, topography, and presence of seedling sources are important factors. Furthermore, spatial patterns inferred from models presented herein suggest a south-westerly pest spread due to favorable environmental factors and potential dispersal events that could be driven by local movement of infested mango propagules or seedlings. Additionally, to make a more biologically sound forecast for FWS, population-driven models that include infestation level or abundance must be developed in case of eventual establishment to new areas. It will also be worth considering the rate of spread from the identified infestation foci for a more robust prediction of the potential pest distribution. In line with this, on the methodological aspect, other SDM modeling frameworks can be explored (e.g., ensemble, random forest). Regarding biological invasion, routes concerning seasonal abundance and aspects of ecological filtering might be also important to account. Furthermore, dispersal mechanisms other than trade (e.g., crawlers by wind) might also be useful in modeling FWS spread in mainland Mindanao. Finally, this study argues that the recent introduction of *C. floridensis* pest establishment is likely probable. Hence, the source of the infestation from the agricultural importation history must be traced to avoid future incursions. As such, close monitoring and placement of plant quarantine measures to ensure safe local movement of mango plantlets from nurseries to local farms to prevent FWS spread and establishment should be seriously considered.

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