Assessing the Potential Susceptibility of *Eucalyptus deglupta* Blume to *Austropuccinia psidii* (G. Winter) Beenken in Mindanao, Philippines

Miles P. Villasan [1], Cristino L. Tiburan Jr. [2], Jessa P. Ata [3], Jayson L. Arizapa [2]

[1] College of Forestry and Natural Resources, University of the Philippines Los Baños, Laguna - mpvillasan@up.edu.ph
[2] Institute of Renewable Natural Resources, College of Forestry and Natural Resources, UPLB, Laguna – {cltiburan,jlarizapa1}@up.edu.ph
[3] Department of Forest Biological Sciences, College of Forestry and Natural Resources, UPLB, Laguna – jpata@up.edu.ph

Keywords: Forest Health, Plant Biosecurity, Maxent, Myrtle Rust; Bagras.

Abstract

Austropuccinia psidii is an invasive fungal pathogen that poses a threat to Myrtaceae species worldwide. While several studies attempted to model its potential distribution, many lack geographical specificity, particularly concerning the Philippines. Despite the absence of occurrence record in the Philippines, the increasing number of reported invasions in Southeast Asian countries highlights the urgency of assessing its potential spread in the country. Environmental conditions from 333 consolidated global occurrence points showed the pathogen's preference for warm climates and moderate temperature fluctuations, alongside a broad tolerance for elevation and precipitation. When applied to Mindanao, results revealed that approximately 62,500 km^2 are environmentally suitable for the pathogen. MaxEnt modeling of *Eucalyptus deglupta* identified about 26,800 km^2 as suitable habitat, particularly in Eastern Mindanao and parts of BARMM. The model's AUC value of 0.7252 indicates fair predictive accuracy, with slope, isothermality, and precipitation of the coldest quarter contributing most to habitat suitability. Overlaying the binary suitability maps for both species showed that around 15,300 km^2, primarily in Eastern Mindanao, are potentially suitable for both *E. deglupta* and *A. psidii*. Davao Region has the highest susceptible area at 5,713 km^2. Bukidnon, Davao de Oro (Compostela Valley), and Agusan del Sur have the largest susceptible areas among the provinces, while Baganga, Davao City, and Laak are the most susceptible municipalities. These findings highlight critical areas that warrant close monitoring for potential myrtle rust outbreaks. Continued research is recommended to refine environmental parameters, enhance model robustness, and support early detection and mitigation strategies.

1. Introduction

The proliferation of invasive pathogens threatens both biodiversity and forest productivity. *Austropuccinia psidii* (G. Winter) Beenken, widely known as myrtle rust, is a globally invasive fungal pathogen that affects all Myrtaceae species. Infected hosts commonly exhibit leaf deformation, shoot-tip dieback, reduced growth, and mortality in severe cases. *A. psidii* was initially identified on *Psidium guajava* in Brazil in 1884. It has since spread to North American regions like Florida, California, and Hawaii, as well as to continents such as Australia, Africa, and Asia. The pathogen disperses through its spores that can be carried by wind, animals, and insects. Additionally, globalization has facilitated its introduction to new regions. Significant ecological and economic losses have been reported in Australia and New Zealand, where it is most prevalent. Consequently, existing research and predictive modeling efforts have predominantly focused on these regions. Although global models of its potential spread have been developed, many lack regional specificity. With recent reports of the pathogen in Asian countries like Japan, Singapore, and Indonesia, the Philippines is potentially at risk of invasion. This risk is particularly concerning for *Eucalyptus deglupta* Blume, the only native *Eucalyptus* species and an economically valuable plantation species in Mindanao. Hence, the present study sought to model high-risk zones for the potential host-pathogen interaction under current climatic conditions by synthesizing environmental suitability maps for both species to support targeted monitoring and preventive action in vulnerable areas.

2. Methods

Guided by the disease triangle framework, the analysis considered three critical components: the presence of the host, the potential presence of the pathogen, and favorable environmental conditions. The presence of both the host and the pathogen is represented by occurrence points, while the environmental conditions are derived from various environmental layers corresponding to these points. Currently, there are no verified occurrence records of *A. psidii* in the Philippines, indicating that the pathogen has not yet been confirmed in the country. Therefore, direct modeling of the pathogen was not feasible. Instead, its environmental envelope was extrapolated from the 333 consolidated occurrence records of the pathogen from countries sharing similar Köppen-Geiger climate classifications with Mindanao. These data points were used to extract relevant environmental parameter ranges, which were then applied to reclassify selected bioclimatic and topographic layers in QGIS to generate potentially suitable areas for the pathogen.

2.1 Study Site

The study focused on Mindanao, the Philippine's second largest island. Mindanao is characterized by diverse topography. It is home to a variety of ecosystems ranging from tropical rainforests and mangroves to agricultural plantations and urban centers. It is of particular interest in this study due to the presence of *E. deglupta*, one of the hosts of *A. psidii*.

2.2 Data Inputs

The study primarily utilized secondary data. Occurrence points for *A. psidii* were obtained from Stewart et al. (2017). These data included records from multiple countries and states such as

Australia, Brazil, Florida, Hawaii, Jamaica, and Puerto Rico. Additional *A. psidii* occurrence points were sourced from iNaturalist, specifically from research-grade observations recorded between 2018 and 2025. Meanwhile, most of the *E. deglupta* occurrence data were provided by Dr. Enrique Tolentino Jr. through the Darwin project, in collaboration with Dr. Cristino L. Tiburan Jr. Supplementary records were also gathered from iNaturalist. All *E. deglupta* occurrence points used in this study were limited to Mindanao. For the environmental layers, topographic and climatic data for the countries and states where *A. psidii* has been recorded were primarily obtained from global datasets.

2.3 Software Used

QGIS was primarily used in this study for map generation, spatial visualization, and geographic data management. It was used to produce potential suitability maps for *A. psidii* and *E. deglupta* and susceptibility map showing potential overlap between the two species. The Point Sampling Tool plugin in QGIS facilitated the extraction of environmental conditions at known *A. psidii* occurrence points. Additionally, QGIS was employed for preprocessing input layers, reclassifying model outputs, overlaying maps for spatial analysis, and calculating the area covered by each classification.

MaxEnt (Philips, Dudík, & Schapire, 2017) is a species distribution modeling software that utilizes presence-only data and environmental variables. The MaxEnt version 3.4.1 was utilized in this study to generate a suitability map for *E. deglupta*, ROC curve, and to perform the jackknife test. Aside from its strong predictive performance, which is comparable to other effective methods, it is also an open-source software, thereby contributing to the cost effectiveness and accessibility of the study.

2.4 Procedural Framework

The study's methodological framework began with the acquisition of key data inputs: occurrence records of *A. psidii* and *E. deglupta* and environmental layers such as WorldClim's bioclimatic variables, Digital Elevation Model (DEM), and soil classification data. The gathered occurrence records were then filtered to enhance data quality. Specifically, *A. psidii* points located outside regions classified as tropical according to the Köppen-Geiger climate classification were excluded.

2.4.1 Extraction of Environmental Conditions Conducive to the Pathogen: Using the Point Sampling Tool in QGIS, environmental values at known occurrence points of *A. psidii* were extracted. These values were consolidated to define the characteristic environmental ranges preferred by the pathogen. Subsequently, the environmental layers of Mindanao were reclassified using these thresholds.

2.4.2 MaxEnt Modeling: Spatial thinning was performed using the spThin package in R to reduce spatial autocorrelation of the *E. deglupta* occurrence points, resulting in a reduction from 185 to 50 spatially independent occurrence records. A correlation analysis of the bioclimatic variables was also conducted to eliminate redundant predictors and retain only informative, non-collinear variables. Using the Pearson correlation coefficient (r) highly correlated variables among the 19 bioclimatic data with a value of $r > 0.8$ were removed (Xu et al., 2019). This resulted in eight bioclimatic variables—bio1, bio2, bio3, bio4, bio14, bio15, bio18, and bio19—along with elevation, slope, and soil, being selected as inputs. All environmental layers were preprocessed to match a consistent spatial extent. To select the appropriate parameters for MaxEnt modeling, the ENMEvaluate function from the ENMeval package in R was used. This package facilitates automated tuning and evaluation of ecological niche models (Kass et al., 2025).

The model's performance was evaluated using the receiver operating characteristic curve (ROC) area under curve (AUC) and jackknife test. The ROC-AUC curve evaluated the model's performance in distinguishing presence and absence points. Meanwhile, the jackknife test was conducted to assess the contribution of environmental variables by examining the model's response in the inclusion or exclusion of respective variables (Phillips, 2017).

2.4.3 Identification of Overlapping Areas: The resulting layer from the MaxEnt modelling, was reclassified into a binary map following the binary threshold value of 0.57, derived from the model's cloglog output to differentiate between suitable and unsuitable areas for *E. deglupta*. The binary layer was overlaid with the environmental suitability map for *A. psidii* to identify overlapping areas that indicate regions where *E. deglupta* may be susceptible to the pathogen.

Figure 1 shows the procedural framework of this study. The green boxes represent the inputs, the pink boxes show the process, and the blue boxes represent the output. Additionally, the blue connecting lines pertain to the process of obtaining the suitability map for *E. deglupta* whereas the red lines represent the process for the suitability mapping of *A. psidii*.

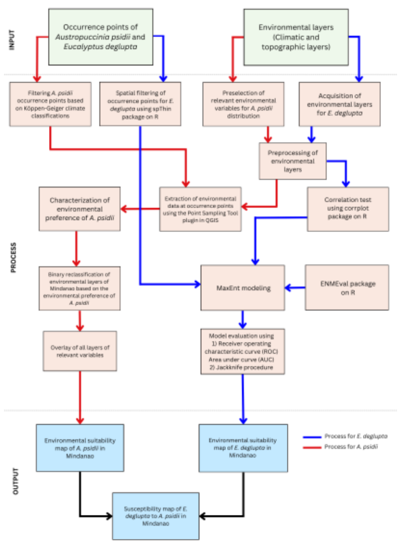

Figure 1. Procedural framework of the study showing the process of generating a susceptibility map of *E. deglupta* to *A. psidii* in Mindanao.

3. Results and Discussion

3.1 Environmental Conditions Associated with the Known Occurrences of *Austropuccinia psidii*

To ensure the applicability of the preferred environmental conditions of *A. psidii* in the Philippine context, the 495 *A. psidii* occurrence points were projected in QGIS and overlaid on the global Köppen-Geiger climate classification raster dataset to characterize their climate types. Figure 2 shows the spatial distribution of climate types across occurrence regions.

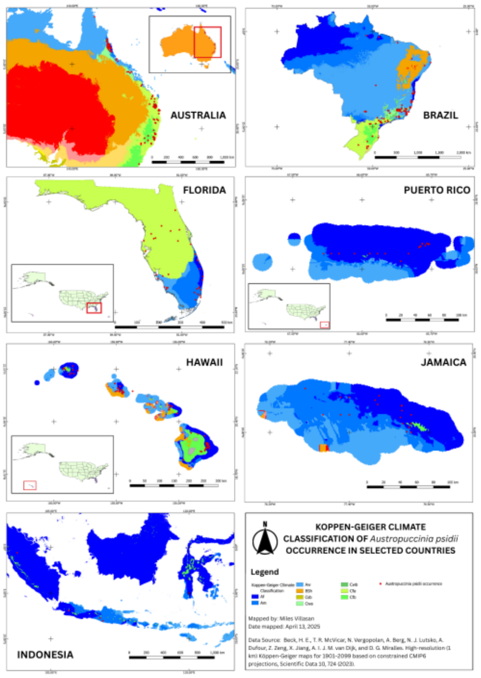

Figure 2. Global occurrence points of *A. psidii* overlaid with the Koppen-Geiger Classification map.

Among the climate classifications, the highest number of *A. psidii* occurrence points were recorded in *Af* (tropical rainforest; count=129), *Aw* (tropical savanna; count=115), and *Cfa* (temperate with no dry season and hot summer; count=108). The *Af* type, also referred to as the wet equatorial climate, has high temperatures of approximately 30°C, abundant rainfall ranging from 1,500 to 10,000 mm annually, heavy cloud cover, and high humidity. This climate type also has minimal seasonal temperature changes (Rafferty, 2011). The *Aw* climate, also referred to as the tropical wet-dry climate, has defined wet and dry seasons, with the majority of rainfall concentrated in the summer months. The *Cfa* type is marked by moderate winters, consistent rainfall, and hot summers. Average temperature in the warmest months often reach around 27°C, while the coldest months remain relatively mild, with temperatures ranging between 5°C and 12°C (Rafferty, 2025). To ensure the applicability of the environmental conditions to the Philippine context, only 333 occurrence points with climate classifications similar to Mindanao (*Af*, *Am*, *Aw*, and *Cfb*) were included in the subsequent analysis. The *Cfb* climate type pertains to the marine west coast climate that exhibits a moderate and stable temperature range with few temperature extremes and generous amounts of rainfall in all months (Rafferty, 2025).

Based on existing literature, the parameters that were included in the extraction of preferred environmental conditions of the pathogen are elevation and slope (Loope, 2010). Bioclimatic variables were also incorporated since studies that used MaxEnt in modeling the distribution of the pathogen often used bioclimatic variables (Stewart et al., 2017; Berthon et al., 2018; Narouei-Khadan et al., 2020). The variables that were used are bio 1 (annual mean temperature), bio 3 (isothermality), bio 4 (temperature seasonality), bio 5 (max temperature of warmest month), bio 7 (temperature annual range), bio 8 (mean temperature of wettest quarter), bio 14 (precipitation of driest month), bio 18 (precipitation of warmest quarter), and bio 19 (precipitation of coldest quarter).

3.1.1 Elevation and Slope: The consolidated occurrence points were found within -3 to 1,318 meters of elevation. Most occurrence points fall within the elevation range of -3 to 97 meters, suggesting that majority of the known occurrence location of the pathogen are found on lower elevation areas. Moreover, the number of occurrence points becomes more evenly distributed at elevation values between 200 meters to 900 meters. The distribution is right skewed, indicating that fewer occurrences were recorded at higher elevations. Although the clustering of known occurrence points at lower elevations may suggest a preference for such areas, it is important to consider the possibility of sampling bias. Lower elevation areas are typically more accessible and may therefore be overrepresented in the datasets. It is also possible that the diseased host plants were mostly located at lower elevations. Existing reports of *A. psidii* have documented its presence at higher elevations, ranging from 600 to 1,200 meters (Loope, 2010; Makinson & Conn, 2014). The slope of the known occurrence points ranges from 0 to 42.70 degrees. Most of the occurrence points were recorded on relatively flat or gently sloping terrain with an average slope of 7.94 degrees.

3.1.2 Bioclimatic Variables: Aside from elevation and slope, bioclimatic variables are another important variable for the pathogen's occurrence as the occurrence of rust pathogens is strongly influenced by temperature, humidity, and solar radiation. For bio1, which pertains to the average temperature of the place over the whole year, the recorded values ranged from approximately 13°C to 27°C. Majority of the occurrence points were recorded in areas with an annual mean temperature of 20 to 26°C. In an experiment by Aparecido, Figueiredo, and Furtado (2003), optimal germination of *A. psidii* urediniospores on rose apple and guava was observed at 21°C, which suggests that relatively mild temperatures are conducive to the early stages of infection. Moreover, Beresford, Shuey, and Pegg (2020) reported that the latent period or the interval between exposure and development of symptoms is shortened under warm conditions with an optimal temperature range of 22 to 28°C. Bio3 pertains to the relative magnitude of daily temperature variation compared to seasonal variation, highlighting the thermal stability of an environment. The majority of occurrence points fall within the 60% to 70% bio3 value range which is typical of tropical areas. For bio4, the values cover a considerable range, from approximately 29 to 497. Majority of the occurrence points are clustered around values ranging from 76 to 170 which may imply that the pathogen is likely to thrive in areas 47 with minimal thermal fluctuations. Bio5 shows that majority of the occurrence points were recorded at around 29 to 31°C. This suggests that a significant portion of the occurrence data are found on areas with consistently warm maximum temperatures during their warmest month. Bio7 quantifies the overall seasonal temperature variation at a location throughout the year. Most of the occurrence points were at locations experiencing a moderate value of 11°C to 13°C. Another bioclimatic variable presented in this study is the bio8 which denotes the average temperature of the wettest three-month period of the year. Its mean temperature is most frequently recorded in the warm range of 25-26°C, with a value extending from 20°C to 26°C. This suggests that the majority of the occurrences' locations experience warm average temperatures during their wettest periods. Meanwhile, bio14 indicates the amount of precipitation, in millimeters, received in the month with the least precipitation. The total amount of rainfall received during the warmest three-month period of the year is denoted by Bio18. Majority of the occurrences experience moderate rainfall during their warmest three months, with peaks around 397-573

https://doi.org/10.5194/isprs-archives-XLVIII-5-W4-2025-253-2026 | © Author(s) 2026. CC BY 4.0 License.

mm. However, the extremely large standard deviation of 273.34 mm and the long tail extending to very high precipitation values indicate high variability. The precipitation of coldest quarter or bio19, pertains to the total amount of precipitation received during the coldest three-month period of the year. The majority of the occurrence points were recorded in areas that experience low to moderate rainfall during their coldest three months, with the highest number of occurrence point being recorded between 33 to 175 mm and with a long tail extending to high precipitation equal to 1,450 mm. Zauza et al. (2014) found a negative correlation between precipitation and the concentration of *A. psidii* urediniospores, noting a decline in airborne spore levels during the wetter months of December to June. While moisture is essential for the pathogen's occurrence, excessive rainfall appears to hinder its spread by washing spores out of the air. This observation aligns is consistent with the results of Lana et al. (2011) and Pegg et al. (2013), who also reported reduced levels of *A. psidii* under high rainfall conditions and attributed this decline to the decreased availability of airborne spores.

3.2 Environmentally Suitable Areas for the Potential Occurrence of *Austropuccinia psidii* in Mindanao

Using the extracted data from the environmental layers, the environmentally suitable areas for *A. psidii* in Mindanao were identified. Figure 3 shows the environmental suitability map for the pathogen that primarily focuses on the overlap of the relevant parameters.

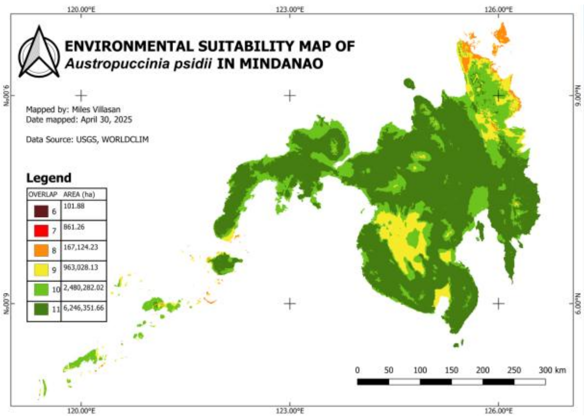

Figure 3. Potential suitability map of *A. psidii* in Mindanao based on its environmental preference.

Habitat suitability refers to the ability of an area to support the survival and persistence of a particular organism (Mendez, 2014). This study specifically focused on potential suitability in relation to environmental factors, hence the use of the term environmentally suitable. The dark green areas on the map represent regions where all eleven relevant environmental parameters overlap, encompassing 62,463 km^2 of Mindanao. This intersection indicates very high environmental suitability for the pathogen, under the assumption that it responds in a comparable manner to all environmental conditions observed at its known occurrence sites. This study primarily focused on areas where all eleven parameters overlap, as these indicate locations that are very highly suitable to the occurrence of the disease. Hence, for clarity in the subsequent discussion, areas categorized as having a "very high" suitability level are referred to as potential "environmentally suitable" areas for the pathogen, as they reflect the convergence of all relevant environmental variables (Figure 4).

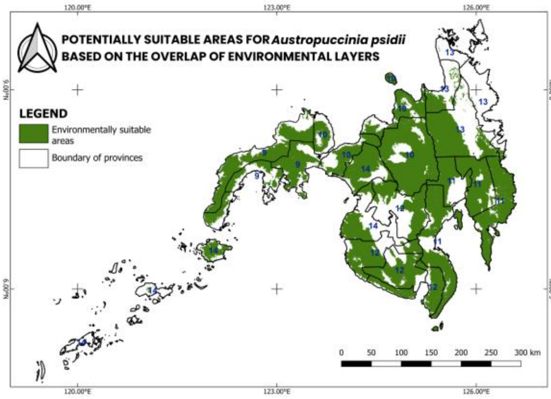

Figure 4. Map highlighting areas in Mindanao where the eleven environmental variables overlap.

As depicted by the map, the majority of region 11 (Davao Region) have areas that are environmentally suitable for the pathogen. Specifically, 15,510.77 km^2 of the region was determined as very highly suitable. In terms of the suitable areas per province, it was revealed that Bukidnon, located in Northern Mindanao (region 10), has the largest area (7,923 km^2) that is very highly suitable for the pathogen. Based on the principle of the disease triangle, there is a high possibility that Myrtle rust will occur in the provinces found to be environmentally suitable for *A. psidii* if susceptible Myrtaceae species are present.

3.3 Maxent Modeling Results for *Eucalyptus deglupta* in Mindanao

The regularization multiplier (value = 2) applied in the model was obtained from the ENMEval package in R, corresponding to the configuration with a delta.AICc value of zero. Through k-fold partitioning, ENMEvaluate generated several combinations of feature classes and regularization multipliers. The model that produced the lowest delta.AICc value served as a basis for parameter selection, since it achieves an optimal balance between predictive accuracy and model complexity while minimizing the risk of overfitting. Among a suite of candidate models, the one with the lowest delta AICc value is considered the best-supported model (Muscarella et al., 2014).

The replicated run type that was used in the modeling is the cross validate, specifically the leave-one-out cross validation, with ten replicates and 10,000 background points, set to 500 maximum iterations following the methodology of Walters et al. (2017). The main output of the MaxEnt model is a continuous map of habitat suitability for *E. deglupta* with values ranging from 0 (unsuitable) to 1 (suitable). Its format is in Complementary Log-Log (Cloglog), which is the default output in MaxEnt ver. 3.4.4 (Smith, 2020). To assess model performance, statistical performance metrics such as the AUC-ROC curve were also generated by the software. Model output validation was carried out by examining the influence of key environmental variables through the jackknife test, variable importance measures, and response curves. These results were then compared with other literature on the ecological preferences of *E. deglupta* to evaluate their ecological plausibility.

3.3.1 Model Validation: The AUC-ROC curve or area under receiver operating characteristic curve is a fundamental metric for assessing the quality of a model. In this study, the average AUC-ROC across the ten replicates was used to evaluate model performance.. A 0.5 value signifies that the model lacks predictive power, while values closer to 1 reflect greater predictive accuracy (Torres et al., 2016). The resulting average training AUC value for the model of *E. deglupta* is equal to 0.79 whereas the test AUC is equal to 0.73. The training AUC uses the same data it was trained on in evaluating the model performance while the test AUC uses the test data. Based on the AUC classification by Swets (1988), the model's AUC value is under the fair classification (0.70-0.80) which implies that it exhibited better performance than a null model, however, it has a fair ability to predict suitable habitats for *E. deglupta*. This interpretation is further exhibited in the average sensitivity vs 1-specificity plot. The average AUC, represented by the red line, is positioned above the graph representing random prediction. This suggests a higher sensitivity or a stronger ability to predict presence points. However, the AUC standard deviation of 0.095 implies an unstable performance among replicates (figure 5).

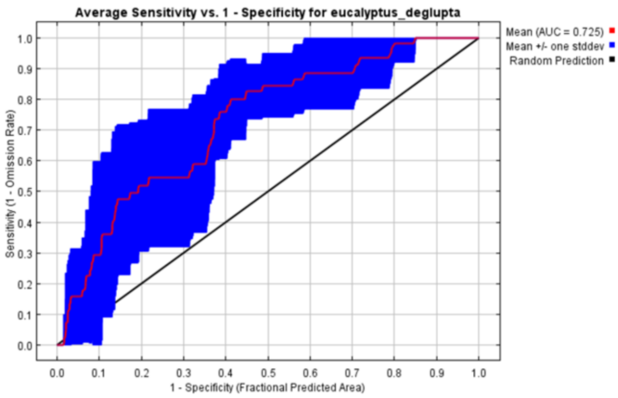

Figure 5. Receiver operating characteristic (ROC) curve of the MaxEnt model for *E. deglupta* showing its ability to distinguish between suitable and unsuitable areas

3.3.2 Analysis of Variable Importance: In terms of percent contribution, among the eleven environmental variables, slope had the highest percent contribution (44.4%), followed by bio3 (14%), soil and bio19 (11%), and bio1 (10%). This implies that these variables had relevant contributions to the improvement of the model during the training process. The remaining variables have relatively low percent contribution, suggesting that they had less direct influence on the model. In terms of permutation importance, slope also obtained the highest value (37.8), followed by bio3 (22.9) and bio19 (13.8), suggesting that these variables had a strong independent effect on the model's predictive accuracy.

3.3.3 Jackknife Test of Variable Importance: The test of variable importance was conducted to evaluate the individual influence of the environmental variables on the model (Figure 6). Among the variables, slope produced the highest gain when used independently, implying that it has the most useful information. Its omission also resulted in the highest decrease in gain, suggesting that it contains information not captured by other variables.

The slope had the largest drop in gain, represented by the shortest green bar, when excluded from the model. This suggests that the model performance becomes worse without this variable since it provides unique information on the prediction of suitable habitats for *E. deglupta*. This variable also obtained the highest percent contribution and permutation importance, highlighting its value in the performance of the model.

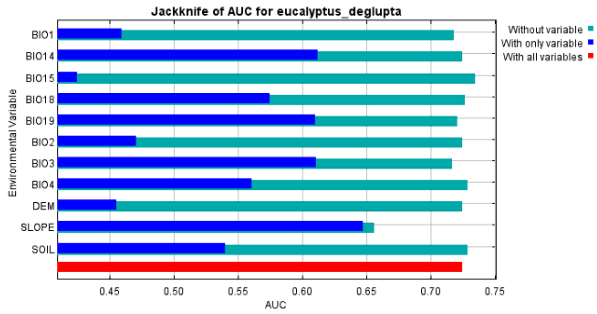

Figure 6. Jackknife test of AUC for *E. deglupta* showing the gain when each environmental variable is used in isolation (blue bars) and the corresponding decrease when variables are excluded (green bars).

Moreover, based on its marginal response curve, the probability of occurrence of *E. deglupta* decreases with slope above 10, suggesting that areas with slope greater than 10 degrees are less suitable to the occurrence of *E. deglupta*. According to CABI (2019), *E. deglupta* is typically found near or within lowland tropical rainforest areas that are growing on relatively flat lands (Butler, 2012). Furthermore, *E. deglupta* is the only *Eucalyptus* species that can thrive in lowland (Orwa et al., 2009).

3.3.4 Response curve of *E. deglupta* to environmental variables: The response curves indicated that habitat suitability for *E. deglupta* increased with higher bio3, bio19, and bio1 values, while it declined with higher slope. Suitability increased when isothermality values exceeded ~ 72%, aligning with the species' preference for stable climates typical of equatorial regions (O'Donnell & Ignizio, 2012). Precipitation levels between 500 mm and 2000 mm during the wettest quarter were associated with higher suitability, consistent with reports of the species thriving in areas with high rainfall (Orwa et al., 2009). For bio1, occurrence was consistently high at 14°C-18°C, declined beyond this range, and stabilized again at 28 °C upward. The optimal tree growth among *Eucalyptus* species was reported at around 18°C to 22° (Queiroz et al., 2020). Suitability decreased with slope, in line with the species' distribution in lowland tropical rainforests. Soil types such as nitisols, ferralsols, and histosols were positively associated with suitability with histosols widely used for planting *Eucalyptus* species (FAO-UN, 2015).

3.3.5 Potential distribution of *E. deglupta*: The potential distribution map of *E. deglupta* in Mindanao was derived from the resulting raster layer of the average MaxEnt model. A binary reclassification of the resulting MaxEnt output was established to distinguish between potential presence or absence areas. The threshold for the reclassification followed the maximum test sensitivity plus specificity value which is equal to 0.5711 based on the MaxEnt result. Liu, White, and Newell (2013) pointed to this threshold as the most efficient. Figure 7 shows the binary suitability map for *E. deglupta*. A great portion of Eastern Mindanao as well as some parts of BARMM, were identified to be suitable for the occurrence of *E. deglupta*. Specifically, a total area of 26,821.84 km^2 was predicted to be suitable.

https://doi.org/10.5194/isprs-archives-XLVIII-5-W4-2025-253-2026 | © Author(s) 2026. CC BY 4.0 License.

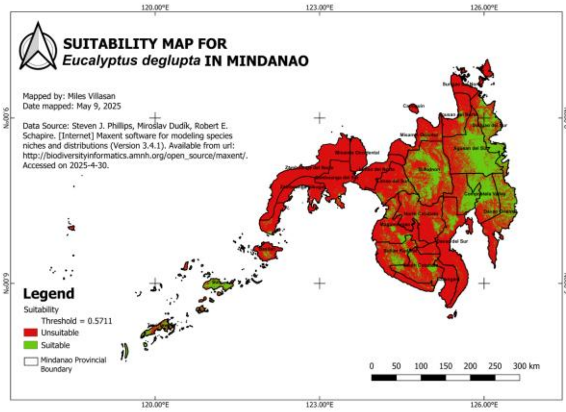

Figure 7. Suitability map of *E. deglupta* in Mindanao generated using MaxEnt.

3.4 Susceptibility of *E. deglupta* to *A. psidii* in Mindanao

The binary habitat suitability map for *E. deglupta* was overlaid with the binary suitability layer for *A. psidii* to identify areas potentially susceptible to the occurrence of Myrtle Rust In this study, susceptibility refers to the likelihood of *E. deglupta* being exposed to *A. psidii*, specifically in areas where the environmental conditions favor the existence of both species. Figure 8 shows the potential susceptibility map of *E. deglupta*. The overlay analysis revealed that high-suitability zones for *E. deglupta* in eastern, central, and certain southern regions of Mindanao coincide with areas that are also environmentally suitable for *A. psidii*. This spatial overlap suggests a heightened risk of Myrtle Rust occurrence in these regions. In contrast, areas classified as not susceptible include locations that are only suitable for one of the two species, or unsuitable for both. Figure 8 shows the potential susceptibility map of *E. deglupta*.

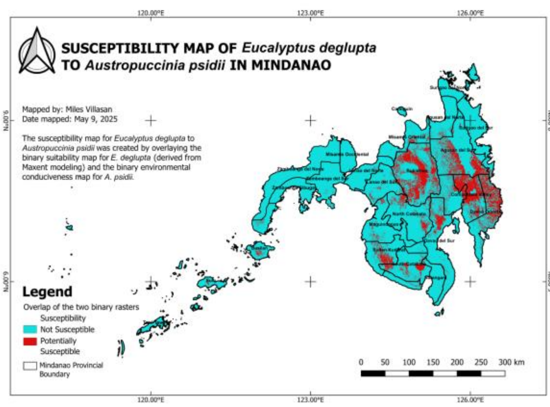

Figure 8. Potentially susceptible areas for *E. deglupta* in Mindanao, shown in red. These areas represent locations where environmental conditions would potentially favor the presence of both *E. deglupta* (host) and *A. psidii* (pathogen).

Mindanao covers an estimated area of 90,000 to 10,000 km^2. As indicated in Figure 9, approximately 20,000 km^2 are unsuitable for both the *E. deglupta* and *A. psidii*. Regarding the host species, 26,821 km^2 were previously mentioned as suitable for *E. deglupta*. Of this, 11,530 km^2 are exclusively suitable for the host but not for the pathogen, indicating areas where the host plant may thrive without the risk of Myrtle rust infection. Notably, 47,177 km^2 are potentially suitable only for the pathogen, suggesting that while *E. deglupta* may not naturally occur in these areas, the introduction or presence of suitable hosts could trigger disease emergence. The overlap between the suitable habitats of both species reveals 15,259 km^2 where environmental conditions favor the occurrence of both *E. deglupta* and *A. psidii*. These overlapping areas are considered susceptible areas, as they represent regions where *E. deglupta* could possibly be exposed to the pathogen.

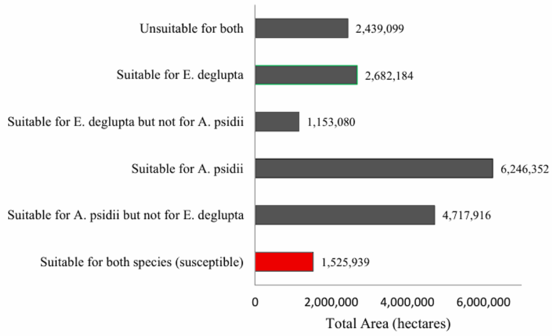

Figure 9. Spatial area (in hectares) of each habitat suitability category for *E. deglupta* and *A. psidii*.

Among all regions in Mindanao, the Davao Region has the largest area of *E. deglupta* susceptible to *A. psidii*. Within this region, Compostela Valley (now Davao de Oro) has the most extensive susceptible area, covering approximately 2,364 km^2. At the provincial level, Bukidnon ranks first in terms of susceptible area, followed by Compostela Valley and Agusan del Sur. At the municipal level, Baganga in Davao Oriental leads with the largest susceptible area (798 km^2).

3.5 Implications on Forest Health

Substantial economic and biodiversity losses are expected as consequences of a Myrtle Rust (*A. psidii*) invasion. This is evident in the current situations in Australia and New Zealand, where the pathogen has caused significant economic damage. In Mindanao, *E. deglupta* is a prevalent species, as further supported by the results of the habitat suitability model. Subsequent analyses revealed that approximately 15,000 km^2 of *E. deglupta* habitat are environmentally susceptible to *A. psidii*. These areas should be closely monitored for early signs of Myrtle Rust infection (Figure 10).

Most areas predicted to be exclusively suitable for *E. deglupta*, are concentrated in the northeastern region of Mindanao, specifically in Surigao del Sur, Agusan del Norte, and Agusan del Sur. Contrarily, almost the entire Sulu Archipelago, including Sulu and Tawi Tawi, was predicted to be environmentally unsuitable for *A. psidii*, suggesting these areas may pose minimal risk of Myrtle Rust invasion. Scattered suitable zones for *E. deglupta* were also predicted across Central Mindanao including parts of Bukidnon, Maguindanao, Davao de Oro, North Cotabato, Lanao del Sur, and Sultan Kudarat. These identified locations present strategic opportunities for establishing *E. deglupta* nurseries or plantations. Prioritizing these areas for development is particularly advantageous given that *A. psidii* poses the greatest threat to young seedlings. As reported by Winzer et al. (2018), the pathogen is especially lethal to juvenile plants, while Silva et al. (2017) emphasized that *A. psidii* primarily infects young leaves and shoots of eucalypt species. Establishing plantations in areas with low environmental suitability for the pathogen may therefore significantly reduce disease risks and support healthier plantation growth.

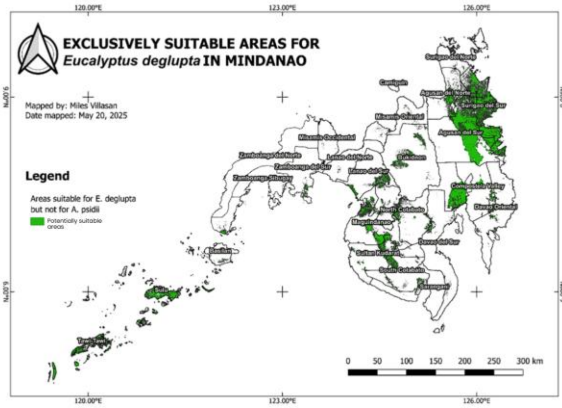

Figure 10. Areas potentially suitable only for *E. deglupta* in Mindanao, defined as locations where environmental conditions favor the host but not the pathogen.

While this study primarily focused on assessing the susceptibility of *E. deglupta,* all species within the Myrtaceae family are still potential hosts of the pathogen. Mindanao, in particular, is home to a diverse range of Myrtaceae species beyond *E. deglupta*, many of which may also be vulnerable to Myrtle Rust. Therefore, it is equally crucial to examine areas that may not be environmentally suitable for *E. deglupta*, yet remain favorable for the occurrence and spread of *A. psidii* as these areas may represent potential hotspots for infection among other Myrtaceae species. Figure 11 illustrates that a vast portion of Mindanao is environmentally suitable for the occurrence of *A. psidii*. This implies that Myrtaceae species inhabiting these areas are potentially susceptible to the invasion of the pathogen, particularly since *A. psidii* is an invasive pathogen not native to the Philippines. As emphasized by Loope and La Rosa (2008), the lack of co-evolution between the host species and the pathogen increases their vulnerability to disease outbreaks.

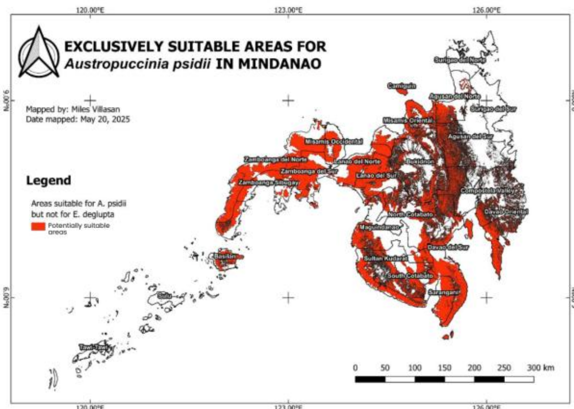

Figure 11. Areas potentially suitable only for *A. psidii* in Mindanao, defined as locations where environmental conditions favor the pathogen but not the host.

4. Conclusion

The assessment of the potential susceptibility of *E. deglupta* to *A. psidii* showed that a large extent of Mindanao is potentially suitable for the occurrence of *A. psidii*. By demonstrating that a large portion of Mindanao has environmentally suitable conditions for *A. psidii*, this study highlights the potential threat that the pathogen may pose, not only to *E. deglupta* but also to other cultivated Myrtaceae species in the region. Given the high economic value of *E. deglupta* in Mindanao's forestry sector, the potential invasion of *A. psidii* places both natural forests and commercial plantations at considerable risk. Young, fast-growing stands are particularly vulnerable, and widespread infection could lead to substantial declines in timber productivity, increased management costs, and long-term impacts on forest health and ecosystem services. Hence, the findings highlight critical areas that warrant close monitoring for potential myrtle rust outbreaks. Continued research is recommended to refine environmental parameters, enhance model robustness, and support early detection and mitigation strategies.

Acknowledgements

The authors would like to extend their gratitude to Dr. Jane Stewart, Dr. Mee-Sook Kim, and John Hanna for providing the global occurrence points for *Austropuccinia psidii*, and to Dr. Enrique Tolentino Jr. for sharing the occurrence points for *Eucalyptus deglupta* in Mindanao, which served as crucial inputs in the modeling process.

References

Aparecido, C., Figueiredo, M., & Furtado, E., 2003. Age and temperature effect on *Puccinia psidii* urediniospores germination collected from rose apple (*Syzygium jambos*) and guava (*Psidium guajava*). *Summa Phytopathologica*, 29(1), 30-33.https://www.cabidigitallibrary.org/doi/full/10.5555/20033100180

Beck, H. E., McVicar, T. R., Vergopolan, N., Berg, A., Lutsko, N. J., Dufour, A., Zeng, Z., Jiang, X., van Dijk, A. I. J. M., & Miralles, D. G, 2023. High-resolution (1 km) Köppen-Geiger maps for 1901–2099 based on constrained CMIP6 projections. Scientific Data, 10, 724. doi.org/10.1038/s41597-023-02378-w

Beresford, R. M., Shuey, L. S., & Pegg, G. S., 2020. Symptom development and latent period of *Austropuccinia psidii* (myrtle rust) in relation to host species, temperature, and ontogenic resistance. *Plant Pathology*, 69(3), 484–494. doi.org/10.1111/ppa.13145

Berthon, K., Esperon-Rodriguez, M., Beaumont, L., Carnegie, A., & Leishman, 2018. Assessment and prioritisation of plant species at risk from myrtle rust (*Austropuccinia psidii*) under current and future climates in Australia. *Biological Conservation*, 218, 154–162. doi.org/10.1016/j.biocon.2017.11.035

Butler, R. A, 2012, July 31. Types of rainforests. World Rainforests. https://worldrainforests.com/0103.htm

CABI, 2019. *Eucalypts deglupta* (rainbow gum). CABI Compendium. https://doi.org/10.1079/cabicompendium.22622

Food and Agriculture Organization of the United Nations., 2015. World reference base for soil resources 2014. https://openknowledge.fao.org/server/api/core/bitstreams/bcdecec7-f45f-4dc5-beb1-97022d29fab4/content

Kass, J. M., Muscarella, R., Pinilla-Buitrago, G. E., & Galante, P. J., 2025, May 1. ENMeval 2.0.5 Vignette. https://jamiemkass.github.io/ENMeval/articles/ENMeval-2.0-vignette.html

Lana, V. M., Mafia, R. G., Ferreira, M. A., Sartório, R. C., Zauza, E. a. V., Mounteer, A. H., & Alfenas, A. C., 2011. Survival and dispersal of Puccinia psidii spores in eucalypt wood products. Australasian *Plant Pathology*, 41(3), 229–238. doi.org/10.1007/s13313-011-0112-4

Liu, C., White, M., &Newell, G., 2013. Selecting thresholds for the prediction of species occurrence with presence-only data. Journal of Biogeography, 40(4), 778–789. https://doi.org/10.2307/23463638

Loope, L., 2010. A summary of information on the rust Puccinia psidii Winter (guava rust) with emphasis on means to prevent introduction of additional strains to Hawaii. http://pubs.usgs.gov/of/2010/1082/

Loope, L., & La Rosa, A. 2008. An analysis of the risk of introduction of additional strains of the rust Puccinia psidii Winter (‘Ohi’a rust) to Hawai’i. Pacific Island Ecosystems Research Center, Open File Report 2008-1008. https://pubs.usgs.gov/of/2008/1008/of2008-1008.pdf

Makinson, R. O., & Conn, B. J., 2014. Puccinia psidii (Pucciniaceae - Eucalyptus Rust, Guava Rust, Myrtle Rust) - a threat to biodiversity in the Indo-Pacific region. *The Gardens' Bulletin, Singapore*, 66(2), 173–188. https://www.cabdirect.org/abstracts/20153075215.html

Mendez, A., 2014, July 8. What is habitability and how is it measured? Planetary Habitability Laboratory. https://phl.upr.edu/library/labnotes/what-is-habitability and-how-is-it-measured

Muscarella, R., Galante, P. J., Soley-Guardia, M., Boria, R. A., Kass, J. M., Uriarte, M., & Anderson, R. P., 2014. ENMeval: An R package for conducting spatially independent evaluations and estimating optimal model complexity for Maxent ecological niche models. *Methods in Ecology and Evolution*, 6(1), 119–128. doi.org/10.1111/2041-210X.12261

Narouei-Khandan, H. A., Worner, S. P., Viljanen-Rollinson, S. L. H., Van Bruggen, A., & Jones, E. E., 2020. Projecting the suitability of global and local habitats for myrtle rust (*Austropuccinia psidii*) using model consensus. *Plant Pathology* (Print), 69(1), 17–27. doi.org/10.1111/ppa.13111

O'Donnell, M. S., & Ignizio, D. A., 2012. *Bioclimatic predictors for supporting ecological applications in the conterminous United States* (U.S. Geological Survey Data Series 691, 10 p.). U.S. Geological Survey. https://pubs.usgs.gov/ds/691/ds691.pdf

Orwa, C., Mutua, A., Kindt, R., Jamnadass, R., & Simons, A., 2009. Agroforestree database: A tree reference and selection guide (Version 4.0). World Agroforestry Centre. https://www.worldagroforestry.org/output/agroforestree-database

Pegg, G. S., Giblin, F., McTaggart, A. R., Guymer, G. P., Taylor, H. L., Ireland, K. B., Shivas, R. G., & Perry, S., 2013. *Puccinia psidii* in Queensland, Australia: disease symptoms, distribution and impact. *Plant Pathology*, 63(5), 1005–1021. https://doi.org/10.1111/ppa.12173

Phillips, S. J., 2017. A brief tutorial on Maxent. American Museum of Natural History. http://biodiversityinformatics.amnh.org/open_source/maxent/

Phillips, S. J., Dudík, M., & Schapire, R. E., 2017. Maxent software for modeling species niches distributions (Version 3.4.1) [Computer Software). https://biodiversityinformatics.amnh.org/open_source/maxent/

Queiroz, T. B., Campoe, O. C., Montes, C. R., Alvares, C. A., Cuartas, M. Z., & Guerrini, I. A., 2020. Temperature thresholds for Eucalyptus genotypes growth across tropical and subtropical ranges in South America. *Forest Ecology and Management*, *472*, 118248. https://doi.org/10.1016/j.foreco.2020.118248

Rafferty, J., 2025. Humid subtropical climate. In Encyclopedia Britannica. https://www.britannica.com/science/humid-subtropical-climate

Rafferty, J., 2025. Marine west coast climate. In *Encyclopedia Britannica*. https://www.britannica.com/science/marine-west-coast-climate

Rafferty, J., 2011. Wet equatorial climate. In Encyclopedia Britannica. https://www.britannica.com/science/wet-equatorial-climate

Silva, R., Silva, A., Rodella, R., Serrão, J., Zanuncio, J., & Furtado, E., 2017. Pre Infection Stages of *Austropuccinia psidii* in the Epidermis of Eucalyptus Hybrid Leaves with Different Resistance Levels. *Forests*, 8(10), 362. https://doi.org/10.3390/f8100362

Smith, T., 2020, June 15. Maxent best practices. Plantarum. https://plantarum.ca/notebooks/maxent/

Stewart, J. E., Ross-Davis, A. L., Graça, R. N., Alfenas, A. C., Peever, T. L., Hanna, J. W., Uchida, J. Y., Hauff, R. D., Kadooka, C. Y., Kim, M., Cannon, P., Namba, S., Simeto, S., Pérez, C. A., Rayamajhi, M. B., Lodge, D. J., Arguedas, M., Medel Ortíz, R., Lopez-Ramirez, M. A., . . . Cleary, M., 2017. Genetic diversity of the myrtle rust pathogen (Austropuccinia psidii) in the Americas and Hawaii: Global implications for invasive threat assessments. *Forest Pathology* (Print), 48(1). doi.org/10.1111/efp.12378

Swets, J.A., 1988. Measuring the accuracy of diagnostic systems. *Science*, 240, 1285–1293.

Torres, A. M., Pulhin, F. B., Lasco, R. D., Tiburan, C. L., Jr., & Eslava, D. F., 2016. Modeling future spatial distribution of Shorea palosapis (Blanco) Merr and Shorea polysperma (Blanco) Merr in Northern Sierra Madre Natural Park using Maxent. *Journal of Environmental Science and Management*, Special Issue 1–2016, 15–30.

Winzer, L. F., Berthon, K. A., Carnegie, A. J., Pegg, G. S., & Leishman, M. R., 2018. *Austropuccinia psidii* on the move: survey-based insights to its geographical distribution, host species, impacts and management in Australia. *Biological Invasions*, 21(4), 1215–1225. doi.org/10.1007/s10530-018-1891-0

Xu, D., Zhuo, Z., Wang, R., Ye, M., & Biao, P., 2019. Modeling the distribution of Zanthoxylum armatum in China with MaxEnt modeling. *Global Ecology and Conservation*, 19, e00691. doi.org/10.1016/j.gecco.2019.e00691

Zauza, E. V., Lana, V. M., Maffia, L. A., Araujo, M. M. F. C., Alfenas, R. F., Silva, F. F., & Alfenas, A. C., 2014. Wind dispersal of Puccinia psidii urediniospores and progress of eucalypt rust. *Forest Pathology*, 45(2), 102–110. doi.org/10.1111/efp.12133