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The Prediction of *Locusta migratoria* (Linnaeus, 1758) Outbreak under Climate Change Scenario in Indonesia

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Abstract

Locusta migratoria (Linnaeus, 1758) is one of the locusts known as important pests of food crops. Outbreaks of this species can cause catastrophic damage to maize, paddy, and many other crops. A species distribution model was used to identify the probability of the locust's current and future potential distribution in the Indonesian archipelago. The study relied on the machine learning method Maximum Entropy (Maxent) Model to forecast the future spread of the species in the Indonesian archipelago and to find the climate variable that influenced the distribution of *Locusta migratoria*. The results showed an Area Under Curve (AUC) value of 0.956 for the *Locusta migratoria* model, indicating a highly reliable model. The important variable for the distribution of this species was precipitation, especially during the dry season. A low amount of rainfall increases the possibility of the species existing and being distributed. Maxent prediction models showed the potential distribution in the southern part of the Indonesian archipelago under both middle and worst-case scenarios for 2070. This model can become one of the baselines for early warning systems, targeted monitoring and surveillance, and the use of specific pesticides or biological control agents to prevent or minimize the harm of *Locusta migratoria* outbreak to agricultural lands in the future.

Keywords: *Locusta migratoria*, maximum entropy, potential distribution, species distribution model

1. Introduction

Indonesia has sufficient agricultural resources to ensure future food security. Pest outbreaks, on the other hand, represent a huge threat to the agriculture sector, particularly in rice fields. One recent pest infestation that has caused significant damage to crop such as corn and rice in Indonesia is the outbreak of migratory locusts (*Locusta migratoria* (Linnaeus, 1758)). Local government is still struggling to control the spread of the pest [1–4]. This outbreak is not unprecedented in history. Large outbreaks of *L. migratoria* were documented from 1997 to 2003, wreaking havoc on agricultural lands in Sumatra, Java, Kalimantan, Sumba, Timor, and Sulawesi. These infections reduced yields and caused crop failures, particularly in Lampung and East Sumba [5,6].

The attacks in the East Nusa Tenggara region are massive, especially on Sumba Island. The locusts spread from the first affected spots in East Sumba to the whole island, where they have become a permanent threat to major food crops such as rice and maize. Many farmers gave up growing rice or corn after two to three failed crops due to locust attacks [7]. The damage caused by *L. migratoria* attacks occurs in various food crops in Indonesia, including rice and corn. On maize, *L. migratoria* begins to attack when the maize plant is 20 days after planting and can continue to affect up to 70% of the plants until the age of 45 days [8].

Denser populations of *L. migratoria* tends to feed more aggressively than those in less dense colonies [9]. *L. migratoria* colonizes and migrates in large groups, consuming the leaves of plants in their path in a short amount of time [10]. These insects typically feed at night until the early morning and then fly back to their colonies [11], making them difficult to control. The migration of *L. migratoria* can extend up to 700 km and cause significant damage to crops [12]. Epidemics are characterized by long-term accumulation of egg production resulting in high population densities, where individuals produce more eggs than normal [13].

Experts have warned that climate change may exacerbate the problem of locust infestation. *L. migratoria* is a warm-climate species; temperature strongly influences its growth, development, and behaviour. Growth and development rates increase with temperature. Rainfall patterns also strongly correlate with the extent of locust attacks on rice and corn plants [14]. The behaviour of this pest is known to be related to climate and rainfall patterns worldwide. Generally, if rainfall intensity is higher, the egg-hatching percentage is lower [15]. The development of *L. migratoria* is influenced by microclimate conditions, seasons, and the balance of other insect populations [16]. The area of barren land filled with weeds becomes a suitable habitat, and low rainfall accelerates the reproductive process [17]. Reproduction generally occurs at the peak of the dry season [18].

Managing insect outbreaks is crucial to ensure food security and sustainable agriculture. To prevent these outbreaks, scientists have been exploring innovative methods such as machine learning algorithms, which can predict insect outbreaks in the intermediate-term future [19]. Species Distribution Models (SDMs) are numerical tools that combine species occurrence or abundance observations with environmental estimates. They are used to gain insights into ecological and evolutionary patterns, as well as to forecast species distributions across landscapes, which sometimes necessitates extrapolation in space and time [20]. SDMs can determine the distribution of favourable settings for a certain species and the places that *L. migratoria* will be displaced from because of climate change. The purpose of this study was to forecast the species' future spread in the Indonesian archipelago and find the climate variable that influenced its distribution.

2. Materials and Methods

The environmental data consists of climate data, including temperature and precipitation. Climate data contains 19 bioclimatic data. The data were collected from the Bioclim website, which provides current information and future climate predictions for 2070 [21]. The data matrices of species occurrence and climatic data were then used to predict the potential distribution of *L. migratoria* (current and future projection) using the Maximum Entropy model (Maxent).

Maxent is widely used to analyze species distribution models. The method uses the machine learning algorithm and the current information of the targeted species only [22]. Maxent, a modeling approach, aims to find the distribution of a species most dispersed or closest to uniform, considering the maximum limits of environmental variables at known locations. The technique used by Maxent, which solely uses presence data, compares the areas where a species has been detected to all the environments that are accessible in the study region [23].

In addition to current climate and information, future analysis was used to predict the species distribution among scenarios. Two scenarios were chosen for the same year in 2070. The RCP 4.5 informs the middle scenario where the climate has been mitigated under 1°C, while the RCP 8.5 shows the business-as-usual scenario [24]. The future data collection was obtained from MIROC5, which has the finest resolution of 1.4008° Latitude × 1.40625° Longitude [25].

All variables use the same spatial information and resolution using the Spatial Analysis program. All climate and elevation data were used at a 30-arc-second resolution, similar to 1 km^2 and extending from 6° North – 11° South and 95° East – 141° East. The prediction was classified into five classes ranging from the lowest probability of spatial distribution (0) to the highest probability (1). Five classifications were used to identify the probability of species distribution in the Indonesia archipelago by five classes, which are Permanently Not Suitable (0.0–0.2), Currently Not Suitable (0.2–0.4), Marginally Suitable (0.4–0.6), Moderately Suitable (0.6–0.8), and Highly Suitable (0.8–1.0). Regions that have a probability equal to or greater than 0.4 are deemed, while the areas with a probability less than 0.4 are considered unsuitable [26].

The projections were overlaid with the administrative map of Indonesia to identify the percentage of the area projected for *L. migratoria* distribution. The future projection was then compared with the current distribution to determine the additional percentage of *L. migratoria* distribution in the future based on both scenarios in 2070.

2.1. Species Occurrence Data

To create the species distribution model, the species occurrence data of *L. migratoria* in Indonesia archipelago was extracted from the Global Biodiversity Information Facility/GBIF (*Locusta migratoria* (Linnaeus, 1758) in GBIF Secretariat with years from 2013 to 2022 [27]. The GBIF data consist of the species name, decimal latitude, and decimal longitude coordinates used in the Maxent application model.

2.2. Environmental/Climatic Data

Previous studies have stated that *L. migratoria* outbreaks are often associated with droughts or coincide with the El Nino period [5,6]. Therefore, climatic factors were used to predict the potential habitat of *L. migratoria* on a local, regional, or global scale. The study sourced its climate variables from the WorldClim Database, which comprises 19 bioclimatic data sets encompassing factors such as temperature and precipitation [21].

2.3. Variable Selection and Statistical Analysis

Cross-correlation calculations aims to show the correlation between predictor variables to minimize issues with multi-collinearity and linearity between predictor variables that could alter the link between the distribution of *L. migratoria* and environmental/climate parameters. If a pair of predictor variables exhibit substantial correlation (correlation coefficient, $r > 0.8$), one predictor variable will be chosen for an additional modeling study.

2.4. Maxent Modelling

The data matrices of species occurrence and climatic data were then used to predict the potential distribution of *L. migratoria* (current and future projections) using the Maximum Entropy model (Maxent). For future analysis, two scenarios were chosen for the same year in 2070. The RCP 4.5 informs the middle scenario where the climate has been mitigated under 1°C, while the RCP 8.5 shows the business-as-usual scenario.

2.5. Model Evaluation

The model's performance was evaluated using the Area Under Curve (AUC) of the receiver operating characteristic (ROC) curve. If the AUC < 0.5 indicates random prediction, 0.5 to 0.7 indicates poor model performance, 0.7 to 0.9 indicates moderate model performance, and AUC greater than 0.9 indicates high model performance [22].

2.6. Change Detection of *L. migratoria* Distribution Area

The projections were then overlaid with the administrative map of Indonesia to identify the percentage of the area projected for *L. migratoria* distribution. The future projection was then compared with the current distribution to produce the additional percentage of *L. migratoria* distribution. The data will be analyzed using Microsoft Excel to produce the percentage area change between the current and future predicted distribution for each administrative area.

3. Results

The SDM model predicts the potential area that has suitable conditions based on the species' presence and distribution [28]. The Maxent prediction model produces a spatial distribution model of the species, which identifies the significant conditions that specify the species' environmental requirements [28,29]. Maxent calculates the probability of the species to distributed across an area by considering the environmental specificity closer to the presence of data information [30,31]. To analyze the model's reliability, the Area Under Curve (AUC) of the Receiver Operating Characteristic (ROC) was used to estimate the model's performance. The AUC result for *L. migratoria* distribution is presented in Figure 1.

The paper presents the evaluation results of the species distribution model using maximum entropy. Figure 1 indicates that the model has high reliability in predicting the potential distribution of *L. migratoria* in the Indonesian archipelago. This means that the model accurately predicts the suitable habitats for *L. migratoria* based on the environmental/climate factors used as predictors.

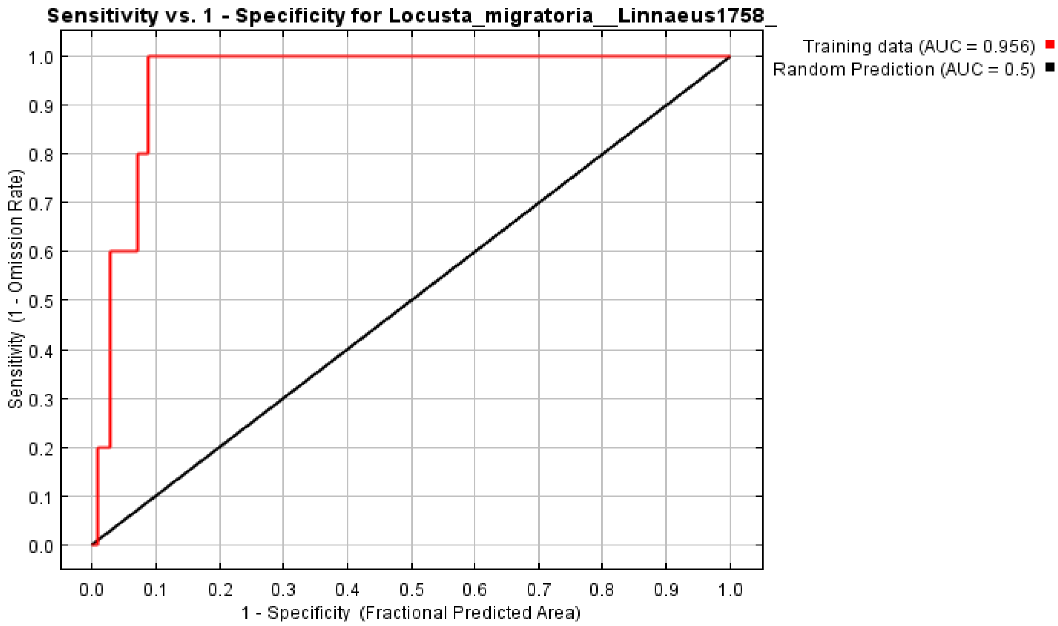

Figure 1. The AUC result of training data (red line) for *L. migratoria* from the Maxent model is 0.956, which is classified as high. This result indicates that the model is reliable.

Figure 2 shows that the migratory locust's habitat suitability has expanded to the northern part of Java, Lesser Sunda (Nusa Tenggara), South Sulawesi, Maluku (Buru and Tanimbar Islands), and southern Papua. These areas are susceptible to the *L. migratory* invasion, especially monoculture agriculture lands that provide abundant food sources for the pests with fewer natural competitors and predators. Figure 2 also shows the current distribution of *L. migratoria*, with probability ranging from 0 to 1 and classified into five categories. Areas with probability > 0.4 are classified as suitable and further divided into highly, moderately, and marginally suitable classes. Probability < 0.4 denotes unsuitable areas.

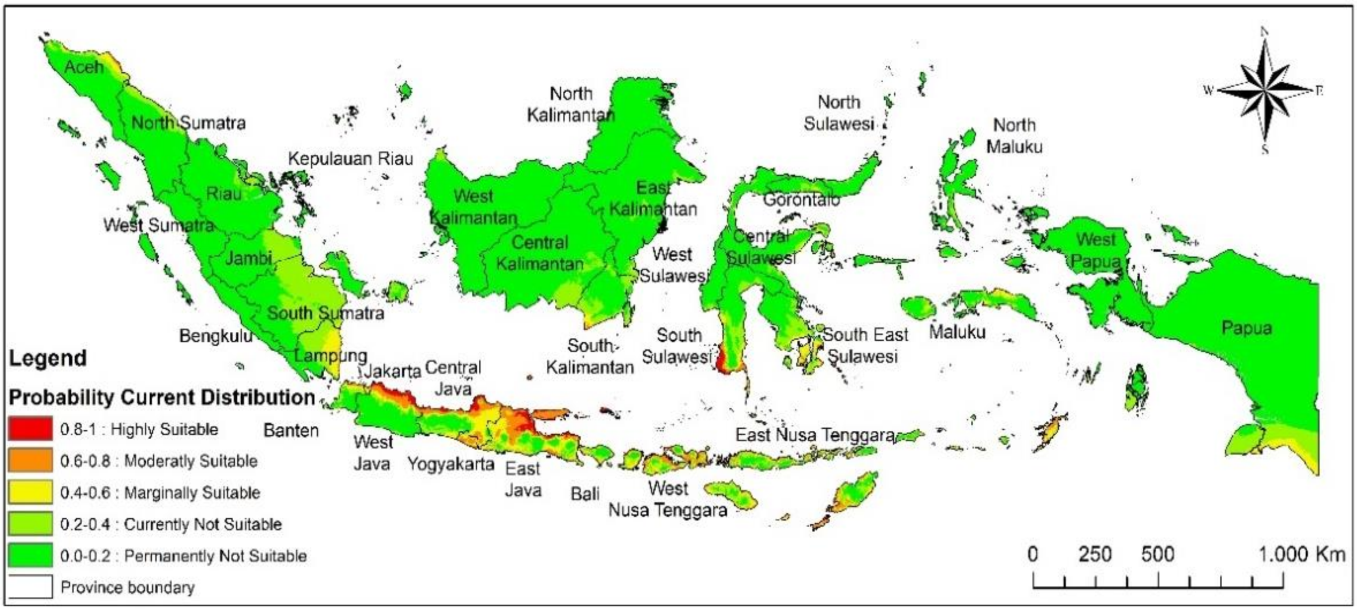

Figure 2. The current probability of *L. migratoria* distribution in Indonesia (warmer colours indicate suitable areas, while green indicates low suitability for species distribution)

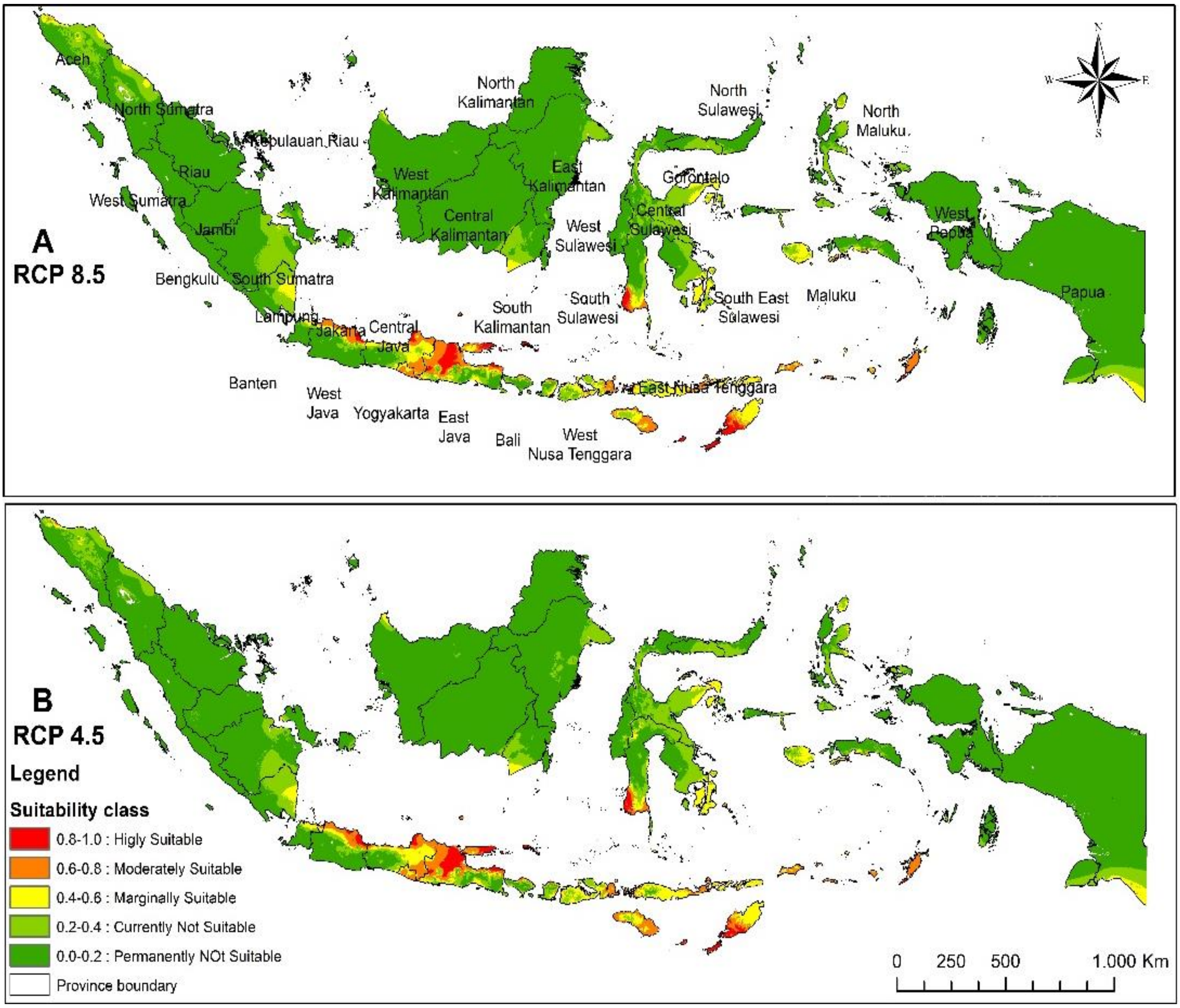

Figure 3. Future distribution at the year 2070 of *L. migratoria* between RCP 8.5 (A) and RCP 4.5 (B) scenarios on raster cell 1 × 1 km^2 in Indonesia. The green colour indicates the low probability while the warm colour shows the highest probability.

Meanwhile, Figure 3 predicts a higher suitability of *L. migratoria* distribution in Java, East Nusa Tenggara, and Sulawesi by 2070 in both RCP scenarios (4.5 and 8.5). It shows a potential increase in the distribution area of *L. migratoria* across the Indonesian archipelago. Most notably, the northern part of Java and Yogyakarta, East Nusa Tenggara, and South Sulawesi will be highly suitable for *L. migratoria* in both RCP 4.5 and RCP 8.5 scenarios. These findings, both current and future predictions, underscore the significance of implementing appropriate measures to manage and control the spread of migratory locusts, especially during the dry season.

Figure 4 illustrates the percentage area of potential *L. migratoria* distribution in 2070, which is projected to increase in most parts of Indonesia, with only a few provinces showing a decrease. The species outbreak is expected to increase by 50% in both RCP 4.5 and RCP 8.5 scenarios. However, the RCP 8.5 scenario, which represents business as usual, predicts a decline in *L. migratoria* distribution below the moderate scenario presented by RCP 4.5.

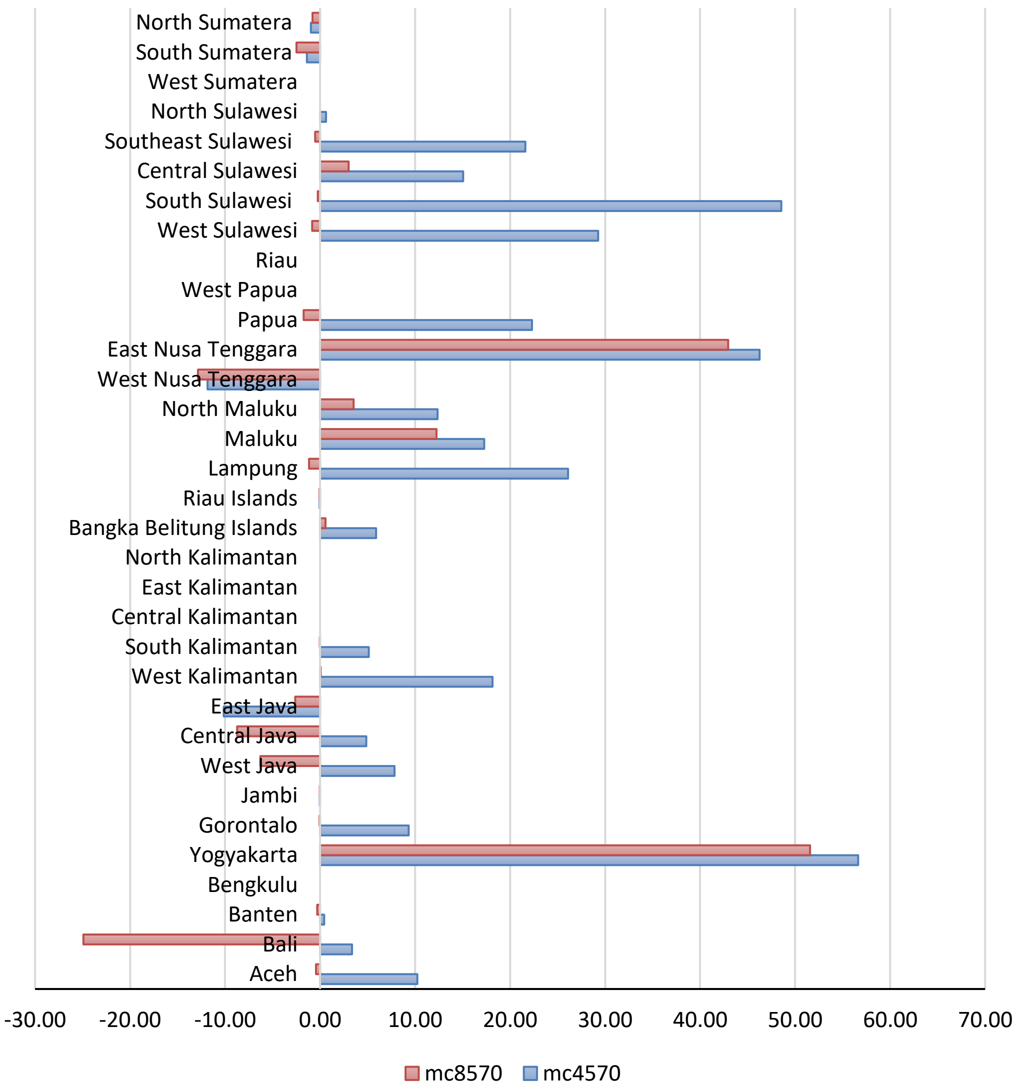

Figure 4. The graphic shows *L. migratoria* distribution in the year 2070 for RCP 4.5 (blue bar) and RCP 8.4 (red bar) scenarios. The graphic indicates the highest distribution of *L. migratoria* located in Yogyakarta while East Nusa Tenggara will not suit the species in the future.

The model predicts the potential current and future distribution of *L. migratoria* using climate variables and elevation as the main factors. Table 1 shows the three primary climate variables that contribute to the species' distribution.

Table 1. Variable percent contribution of *L. migratoria* distribution across Indonesia

No.	Variable	Percent contribution	Description
1	bio14_a	41.3	Precipitation of Driest Month
2	bio18_a	27.7	Precipitation of Warmest Quarter
3	bio15_a	23.6	Precipitation Seasonality

Source: Maxent percent contribution analysis.

The analysis of the model identified three key variables that significantly contributed to the suitable habitat of *L. migratoria*: precipitation of the driest month (bio14), precipitation of the warmest quarter (bio18), and precipitation seasonality (bio15). Interestingly, the patterns showed similarities between the precipitation of the driest month and the warmest quarter, where lower precipitation in both variables led to more favourable environmental conditions. Conversely, higher precipitation seasonality seemed to contribute to a more suitable habitat.

4. Discussion

Indonesia has grappled with recurrent migratory locust infestations since 1998. A significant agricultural pest in tropical regions, the migratory locust poses a major threat to crops in numerous countries [5,32]. To address this persistent issue, policymakers must shift from reactive pesticide-based approaches to proactive, long-term strategies. Species distribution models offer a valuable tool for predicting current and future locust distribution patterns in Indonesia. By analyzing key factors like climate and elevation, these models can pinpoint areas susceptible to infestations. Through with this knowledge, policymakers can implement targeted pest control measures, optimizing resource allocation and minimizing environmental impact.

As Table 1 indicates, precipitation significantly influences the distribution of *Locusta migratoria* across the Indonesian archipelago. This finding aligns with previous research demonstrating a correlation between *L. migratoria* outbreaks and low-precipitation periods, especially during the dry season [14]. Prolonged dry conditions likely contribute to increased egg accumulation in the soil, leading to synchronized hatching upon subsequent rainfall [33]. This phenomenon is similar to the reproductive behavior of Schistocerca cancellata, which enters a diapause during dry periods and resumes activity with the onset of rain [34].

On the other hand, high or strong precipitation seasonality could indicate a higher deviation of water vapour between seasons [35]. Strong precipitation seasonality in Indonesia may occur because of monsoon and ocean-atmosphere interaction, characterized by high temperatures in the dry season and high precipitation during the rainy season [36,37]. Therefore, *L. migratoria*'s *t*endency to reproduce and accumulate eggs in the dry season, which is related to the high-temperature period, could correspond with the outbreak of the pest and strong precipitation seasonality.

Insect pests, including migratory locusts, pose a significant threat to global agriculture, causing substantial crop damage and yield losses. To effectively combat these pests, a multifaceted approach is essential. Early warning systems, targeted monitoring, and judicious pesticide use are crucial components. However, traditional chemical pesticides often have detrimental environmental and health impacts. As a result, there's growing interest in eco-friendly alternatives like biological and integrated pest management. These methods, which utilize entomopathogens such as fungi, bacteria, viruses, and nematodes, offer precise, safe, and sustainable solutions for pest control [38].

Photorhabdus luminescens, a type of bacteria, is a natural enemy of the African migratory locust or *Locusta migratoria migratorioides*, and its cell-free filtrate has shown promise as a biocontrol option due to its carbohydrate hydrolyzing enzyme activities [39]. In a similar experiment involving *L. migratoria* larvae, Wu and Rozlomiy [40] applied a suspension emulsion of the entomogenous fungus *Beauveria bassiana* in a controlled laboratory setting, which resulted in a mortality rate of over 70% after 10 days for lawn land. However, further studies are necessary to determine the effect of entomopathogens treatment on gramineae group crops, especially to find the proper agents with higher and faster mortality rates.

Learning from the locust outbreak in Africa, planting leguminous crops like soybean and fruit crops that migratory locust dislike eating, such as grape and watermelon, may help to mitigate locust outbreaks and minimize crop damage [41]. Since migratory locusts favor plants such as rice, maize, sorghum, and others from the Gramineae group, further studies to combine these crops with other plants that locusts dislike are necessary. Additionally, promoting diversified farming practices and reducing reliance on monoculture agriculture can help reduce crops' vulnerability to pest infestations.

5. Conclusions

This research indicates that the northern part of Java, Lesser Sunda, South Sulawesi, certain islands in Maluku (Buru and Tanimbar), and southern Papua are vulnerable to locust invasions. Yogyakarta and East Nusa Tenggara were identified as the highest-risk areas in both RCP 8.5 and 4.5 climate scenarios. Among the factors, precipitation plays the most significant role in influencing the likelihood of pest expansion in the future.

Author Contributions

MHS, S: Conceptualization, Methodology, Software, Investigation, Writing - Review & Editing; **MHS, S, EP, HIJ, RK**: Acquisition of data; **MHS, S, HIJ, EP**: Analysis data; **MHS, RK, NH, AH**: Drafting the manuscript; **MHS, HK, YH, EEWH, NH, AH**: Writing - Review & Editing.

Conflicts of Interest

There are no conflicts to declare.

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