Prediction of potential climate change impacts on the geographic distribution shift of *Casuarina junghuhniana* and *C. equisetifolia* in Southeast Asia

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Abstract. *Khairunnisa H, Dewi MAK, Faqiih MAH, Putrayuda MR, Nugroho GD, Indrawan M, Sutarno, Sugiyarto, Sunarto, Supriatna J, Nursamsi I, Gunawan, Pradhan P, Setyawan AD. 2023. Prediction of potential climate change impacts on the geographic distribution shift of* Casuarina junghuhniana *and* C. equisetifolia *in Southeast Asia. Biodiversitas 24: 6360-6371.* Global warming, driven by various anthropogenic activities, leads to an increase in earth's surface temperatures, exerting a profound influence on global climate patterns. This phenomenon significantly impacts the growth patterns of various plant species, including *Casuarina equisetifolia* L., commonly known as sea cypress, and *Casuarina junghuhniana* Miq., referred to as mountain cypress. The primary objective of this study is to assess the potential repercussions of climate change on the distribution of these two species within Southeast Asia. To achieve this goal, the study utilized the MaxEnt modeling approach, incorporating key factors such as bioclimatic conditions, soil characteristics (edaphic factors), and UV radiation levels. Present study considered three distinct time intervals (2030, 2050, and 2080) while exploring four diverse climate change scenarios (RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5). The findings of this investigation reveal that both *C. equisetifolia* and *C. junghuhniana* are susceptible to alterations in the extent of suitable habitat distribution, which result in shifts in their geographic ranges due to evolving climatic conditions. Initially, the habitat distribution encompassed an area of only 652,819 km^2, accounting for 15.65% of the suitable habitat for *C. equisetifolia*, and 30,132 km^2, representing 0.7% of the suitable habitat for *C. junghuhniana*. However, by the year 2080, the habitat range for *C. equisetifolia* is projected to expand significantly to cover 755,082 km^2 (18%) under the RCP 4.5 scenario. In contrast, *C. junghuhniana* is expected to experience a notable reduction, with its suitable habitat shrinking to 25,332 km^2 (0.6%) under the influence of RCP 8.5. Notably, these shifts are characterized by a southeastward migration of *C. equisetifolia* towards Indonesian Borneo from Malaysian-Indonesian border and an eastward shift of *C. junghuhniana* towards the east of Sulawesi from the Gulf of Bone. These findings highlight the dynamic nature of species distributions in response to changing climatic conditions, emphasizing the need for proactive conservation efforts and adaptive management strategies to mitigate potential ecological impacts.

Keywords: *Casuarina*, core distribution shift, MaxEnt, Representative Concentration Pathways, species distribution models

INTRODUCTION

Casuarina junghuhniana Miq. and *C. equisetifolia* L. are commonly known as mountain cypress or mountain ru (*cemara gunung*) and sea cypress (*cemara* or *cemara laut*). Both *C. junghuhniana* and *C. equisetifolia* are important for conservation efforts because they represent a unique and distinct lineage (Friis 1980; Golam and Araki 2010). Both can grow in arid environments and lack nitrogen, but with different preferences, i.e. highlands for *C.*

junghuhniana and lowlands for *C. equisetifolia*. In addition, the natural regeneration of *C. equisetifolia* is relatively low because of its small seed viability, which ranges from 7-16% (Eze and Ahonsi 1993). While, *C. junghuhniana* is a dioecious plant, it requires two different individuals (male and female) for regeneration (Pauldasan et al. 2023). However, both *C. junghuhniana* and *C. equisetifolia* offer various benefits to the environment and the local economy. In the research of Siregar et al. (2022), it was revealed that the people of the south coast of Bantul,

Indonesia highly value *C. equisetifolia* for its numerous benefits. As a result, 90% of the people in that area actively plant *C. equisetifolia*. These efforts also contribute to mitigating natural disasters in coastal areas (Purwantara et al. 2019). Furthermore, it was mentioned that *C. equisetifolia* plays a role in improving the microclimate of sandy coastal lands (Harjadi 2017). Meanwhile, *C. junghuhniana* provides economic benefits such as being used as building materials, firewood, Christmas celebrations, and charcoal production (Siregar et al. 2022). The wood from *C. junghuhniana* is in great demand because of their quality, especially for constructing buildings on stilts (Sallata 2016), and also for traditional feast ceremonies (Ambalinggi 2021).

Casuarina junghuhniana and *C. equisetifolia* are two species of *Casuarina* trees with broad distribution in various regions within tropical climates. Their specific locations are influenced by several environmental factors, including rainfall and temperature (Nicodemus 2015). *C. junghuhniana* tends to be found in areas with relatively high rainfall and high humidity. This species thrives in regions with extended rainy seasons and fairly high rainfall intensity. On the other hand, this species has also high tolerance for oxygen-deficient conditions, making it suitable for arid areas (Yulianto et al. 2019). It exhibits adaptability to varying temperature ranges, including areas with warm to moderate temperatures (Diagne et al. 2013). In contrast, *C. equisetifolia* is commonly found in areas with lower rainfall. This species grows well in areas characterized by prolonged dry seasons and lower air humidity (Djighaly et al. 2018). These differences in habitat preferences reflect the adaptation of both species to specific environmental conditions that allow them to grow and develop optimally (Ai et al. 2022). In Java, *C. junghuhniana* grows naturally at 1200-3100 m asl. mainly in montane fire-climax forests, but in the Lesser Sunda Islands it comes down to sea level. While, *C. equisetifolia* is a typical pioneer of sandy coasts, but has been reported at up to 800 m altitude in the Philippines (Suhardi 1998). It may be noted that both climate change and anthropogenic activities can significantly influence distribution of *C. junghuhniana* and *C. equisetifolia*.

Climate change can impact species distribution, primarily because climate is a crucial factor determining the environmental conditions in which species can survive (Li et al. 2018). The observed trends of rising global temperatures and shifting rainfall patterns directly influence the suitability of habitats for various species. Consequently, these changes can trigger shifts in the geographical boundaries of species, either toward the north/south or to higher or lower elevations (Wang et al. 2021). Species Distribution Models (SDMs) serve as valuable tools to identify regions with the most suitable environmental conditions for specific species. However, it's essential to recognize that these models provide estimates rather than exact predictions. They are based on current environmental conditions and need to be regularly updated with the latest data, accounting for ongoing environmental dynamics, to enhance the accuracy of predictions (Wang et al. 2021). The purpose of this study was to model the current geographical distribution of *C. junghuhniana* and *C. equisetifolia* in the Southeast Asian region. Additionally, the study aims to project the future distribution of these species under the influence of climate change.

MATERIALS AND METHODS

Study area

The study was conducted in Southeast Asia focusing on the two species of *C. junghuhniana* and *C. equisetifolia*. The biodiversity rich region of Southeast Asia includes several countries like Indonesia, Malaysia, Thailand, the Philippines, Singapore, Vietnam, Laos, Myanmar, Cambodia, East Timor, and Brunei Darussalam. Southeast Asia provides habitat for tropical rainforests, which are among the largest in the world and host an array of biodiversity, including unique variety of plants, animals, and microorganisms. Geographically, this study covered an extensive area, spanning approximately 4°N to 6°S latitude and 114.5°E to 126°E longitude (Figure 5), covering about 4,687,481 km^2 of land. The climatic conditions prevailing in Southeast Asia are characterized by high humidity and year-round tropical heat. Rainfall in the region exhibits variability, and the climate is generally classified as monsoonal, featuring distinct wet and dry seasons (Leinbach and Frederick 2015). Furthermore, the region's topography, situated on a plateau, results in milder temperatures and drier landscapes.

Materials

Casuarina junghuhniana (Figure 1.A-B)

Casuarina junghuhniana, a gymnosperm commonly referred to as mountain cypress (Figure 1.A-B), predominantly thrives in mountainous regions. It exhibits distinct characteristics, including a maximum height of 35 meters, a diameter ranging from 30-50 cm, and an open crown shape. The bears cone-shaped fruit of the orthodox type (Ambalinggi 2021). *C. junghuhniana* firewood has a specific gravity of 1.12 placing it in strength class I and durability class II (Putra and Listyanto 2021). The leaves of this plant resemble needles, arranged in an alternating or opposite fashion. It has dioecious reproductive system, with male cones measuring 7.3±0.04 cm in length and female cones measuring about 1.3±0.04 cm (Pauldasan et al. 2023).

Naturally, *C. junghuhniana* grows at elevations ranging from 550-3,100 meters above sea level (m asl.), although in some places it can also grow in less than 100 m asl. areas. Habitats where this plant occurs generally experience temperatures between 10°-20°C, with an average annual rainfall of around 700-2,000 mm (Ambalinggi 2021). *C. junghuhniana* displays adaptability to various habitats, such as steep slopes, valleys, mountainous terrains, soils with rock substrates, and volcanic crater valleys. In Indonesia, this species is prevalent in many forests such as the foothills of Mount Sumbing and Mount Sindoro (Dishutbun Wonosobo 2019).

Figure 1. *Casuarina junghuhniana* (A and B) and *C. equisetifolia* (C and D). Source: GBIF

One notable attribute of this species is its capacity to fix nitrogen, a vital trait in tropical regions (Pauldasan et al. 2023). Moreover, it exhibits rapid growth and demonstrates a high tolerance for oxygen-deficient conditions, making it suitable for cultivation in arid areas (Yulianto et al. 2019). It is particularly beneficial for planting in landslide-prone terrain. In addition, *C. junghuhniana* contributes to soil fertility enhancement and soil rehabilitation, while its logs serve as valuable firewood material for papermaking and aid in soil conservation.

Casuarina junghuhniana is a native Indonesian plant that grows in Java (especially East Java) and the Lesser Sunda Islands (Bali and Nusa Tenggara) from Bali to Timor and Wetar. It has been introduced to Southeast Asia (India, Pakistan, and Bangladesh) and East Africa (Kenya and Tanzania). Male hybrid plants with *C. equisetifolia* were introduced to Thailand around 1900, and their offspring were brought from there to India in the early 1950s (Pinyopusarerk 1997). Another source states that *C. junghuhniana* was introduced to India in 1996 as an important species in agroforestry, and wood from that species has significant potential for use in the pulp and paper industry (Parthiban et al. 2014).

Casuarina equisetifolia (Figure 1.C-D)

Casuarina equisetifolia, commonly known as sea cypress, is a plant that thrives in coastal and marine areas (Farma et al. 2018). It can be found in sandy 6beach areas as well as rocky coastlines (Figure 1.C-D). Along the coastlines, this plant provides shade and enhances aesthetic beauty of beach areas, creating a cooler microclimate (Sukma and Spanton 2021). This plant possesses remarkable defense mechanism against waves and abrasion, making it resilient in coastal settings (Alisani et al. 2022). *C. equisetifolia* can withstand wind speeds and improve soil conditions in sandy soil with high salt content. It grows at altitudes of up to 800 m asl., can withstand drought conditions for 6-8 months. Its habitat typically experiences temperatures ranging from 26°C-33°C (Nahak et al. 2022). This plant can thrive in areas with annual rainfall of around 200-3,500 mm (Hutasoit et al. 2015), and humidity levels ranging from 84-100% (Harjadi 2017).

Casuarina equisetifolia belongs to deciduous plants and exhibits coniferous appearance. It features straight stem with a rough texture and an irregular, open crown. The trunk bears horizontal branches which can reach height of approximately 25 m (Essien et al. 2016). The plant's leaves are greyish-green and resemble pine needles. The small-scale leaves consist of 6-8 strands of leaf scales arranged in circle fashion (Hitakarana 2017) and are easily shed when subjected to strong wind. The flower of *C. equisetifolia* is brown and small, while fruits are cone-shaped, spherical, and relatively small (Hitakarana 2017). It is a monoecious tree, male and female flowers are on same plant. The male flowers are arranged in spikes, 0.7–4 cm long, while female cones are 1–2.4 cm long (Boland et al. 2006).

The native distribution of *C. equisetifolia* includes regions around the Pacific islands, Oceania, and countries in Southeast Asia. However, its growth is influenced by factors such as actinorhizal symbiosis and mycorrhizal associations that aid in phosphorus acquisition. Additionally, *C. equisetifolia* has been cultivated along the southeast coast of China since the 1950s. Currently, the area covered by *C. equisetifolia* plantations in China has reached 300,000 ha (Wang et al. 2013).

Procedure

Event data collection

This study used a combination of primary data and secondary data. Primary data was obtained from direct observations in Java, Indonesia during June-July 2023. To ensure accuracy, 20 coordinate points were recorded, with ten coordinates corresponding to each of the two species. The geographical coordinates were precisely determined with the help of Google Maps. Field observations were meticulously carried out to mitigate any potential data biases. Sampling locations were selected based on the presence of the two species, taking into consideration the distribution and evenness across the island of Java. Concurrently, secondary data was obtained from the Global Biodiversity Information Facility (GBIF) (http://www.gbif.org) database. This source provided information on a total of 261 occurrences of *C. equisetifolia* and 38 occurrences of *C. junghuhniana* in

Southeast Asia. The gathered data underwent geometrical validation using Google Earth Pro and was subsequently converted into CSV format for further analysis. Both the primary data and secondary data sources carry inherent risk of bias and errors during data processing and species presence determination (Kramer-Schadt et al. 2013). To address this, sampling bias correction was conducted as an important step to minimize its potentially strong influence on modeling predictive ability and subsequent interpretation (Kramer-Schadt et al. 2013; Fourcade et al. 2014). The sampling process was executed with the help of ArcMap 10.5 with SDM Toolbox v2.5, employing with samples and MCP (MaxEnt Tools) buffer to techniques to reduce bias, with a buffer distance of 10 km. The utilization of buffered MCP samples aimed to mitigate the potential for data bias that could result in inaccurate species distribution findings (Evans and Brown 2017).

Current conditions of bioclimatic and environmental variables

The study incorporated a total of 19 bioclimatic variables, two edaphic variables and five environmental variables known to significantly influence the growth of *C. junghuhniana* and *C. equisetifolia* in Southeast Asia (Table 1). The edaphic data includes information on soil organic carbon content and soil pH levels, sourced from International Soil Reference and Information Centre (ISRIC) accessible at https://data.isric.org/geonetwork/ (Hengl et al. 2017). Subsequently, the acquired raster data underwent processing in ArcMap 10.5, involving operations such as resampling, as well as cropping and masking according to the boundary of the study area. The data was then converted into MaxEnt readable (.asc) format. Furthermore, secondary data was drawn from bioclimatic datasets available at Worldclim web platform (https://www.worldclim.org/). Specifically, UVB1, UVB2, UVB3, and UVB4 were selected from the global UVB radiation dataset referred to as gIUV (https://www.ufz.de/gluv/). The gIUV dataset provides critical insights into the distribution of ultraviolet-B radiation, complementing the bioclimate dataset (Beckmann et al. 2014). Additionally, historical climate data was employed a spatial resolution of 2.5 minutes (equivalent to approximately 20.25 km²) (Fick and Hijmans 2017). To model species distribution, this study utilized a combination of bioclimatic and environmental variables. Reducing the number of covariates was considered important for enhancing the accuracy of species distribution estimation, as excess variables can introduce complexities to the modeling process in MaxEnt, especially when the variables are closely related (Yoon and Lee 2021). In addition, Principal Component Analysis (PCA) was employed as an analytical tool to refine the dataset. After the variable reduction process, the study overall incorporated two edaphic variables (organic carbon and soil pH), six bioclimatic variables (bio4, bio5, bio8, bio9,

and bio10, bio11), and five topographic/environmental variables (elevation, UVB1, UVB2, UVB3, and UVB4).

Future climate projection

This study incorporated a future climate design by simulating species distribution under various Representative Concentration Pathways (RCPs). Future climate data was obtained from the International Center for Tropical Agriculture (CIAT) and The Program on Climate Change, Agriculture and Food Security (CCAFS) (accessible at https://www.ccafs-climate.org/data_spatial_downscaling/) (Navarro-Racines et al. 2020). In addition, the study utilized climate data from mohc_hadgem2_as model (Hadley Center Global Environmental Model 2 Earth System), selecting the appropriate scenarios based on the required specifications. The study examined three time periods: 2030, 2050, and 2080, across multiple RCP models, including RCP 2.6, 4.5, 6.0, and 8.5 belonging to CMIP5 (Coupled Model Inter-comparison Project Phase 5) (Mohan and Bhaskaran 2019). The choice of these three time periods enabled the assessment of climate change impacts on the distribution of *C. junghuhniana* and *C. equisetifolia* in Southeast Asia at different future points. Furthermore, the study considered other topographic/environmental variables, including elevation/altitude, soil organic carbon, soil pH, and UVB1-4. These variables were assumed to remain relatively stable and not undergo significant changes due to increased greenhouse gas concentrations. To comprehend the effects of climate change at both local and global scales, data from the Global Climate Model (GCM) was incorporated into the analysis. However, it's crucial to note that climate change prediction models, while highly informative, cannot serve as the sole reference due to potential biases arising from differences in spatial resolution and numerical schemes during data processing (Teutschbein and Seibert 2013).

Table 1. Environment variables used to build the model

Code	Name	Units
bio_4	Temperature seasonality	SD × 100
bio_5	Maximum temperature of the warmest month	C×10
bio_8	The mean temperature of the wettest quarter	C×10
bio_9	The mean temperature of the driest quarter	C×10
bio_10	The mean temperature of the warmest quarter	ÿC×10
bio_11	The mean temperature of the coldest quarter	C×10
soc	Soil organic carbon	-
ph	Soil pH	-
lev	Elevation	m asl
uvb1	Annual mean UVB	J m-2 day-1
uvb2	UVB seasonality	J m-2 day-1
uvb3	Mean UVB of lightest month	J m-2 day-1
uvb4	Mean UVB of lowest month	J m-2 day-1

Model development

To predict the current distribution of *C. junghuhniana* and *C. equisetifolia* in Southeast Asia and their potential range shift due to climate change in the future, this study utilized MaxEnt version 3.4.4 (accessible at https://biodiversityinformatics.amnh.org/open_source/maxent/) (Phillips et al. 2009). MaxEnt is a widely-used software tool for species distribution modeling, capable of making predictions based on Presence-Only (PO) data (Phillips and Dudik 2008). MaxEnt offers a range of optional features to streamline data analysis and adjust results as needed. For this modeling process, several specific settings were applied, which include (i) setting maximum iterations for model at 5,000 for each run to ensure sufficient converging time, (ii) setting convergence threshold at 1×10^{-6}, (iii) using "cross-validation" type replication process, which involves performing 10 replicated runs and taking average value of their results. Furthermore, to "cross-validate" the model, the data was split into 10 partitions. Each partition was used to train the model 10 times, with 90% of the data used for training and the remaining 10% for testing. This process was repeated for each partition.

Core distribution shift

In this study, a Python-based GIS toolbox 'SDM toolbox', was used to summarize the major distribution shifts (Brown 2014) in the habitats of *C. junghuhniana* and *C. equisetifolia* between two binary models: The present and future scenarios. Furthermore, additional assessments were made regarding alterations in the suitable habitat. A centroid line is computed by averaging the latitude and longitude of the binary input pixels, and subsequently used to represent the central point of the species range and to indicate the direction of change. Subsequently, the study used RCP year 2080 to identify the most pronounced shifts in the geometric distribution centers, as this period is anticipated to be the most affected by climate change (Setyawan et al. 2018).

Data analysis

The output generated by the MaxEnt program consists of continuous data that illustrates the potential distribution of habitats along a linear scale, ranging from lowest (0) to highest (1) (Phillips and Dudik 2008). Furthermore, MaxEnt calculations are based on the relative contributions of covariates such as bioclimatic variables, which significantly influence the prediction outcomes. Alternative estimations of the variables listed in MaxEnt are also important for generating jackknife test results. The later test results show which variables provide the most valuable information and which ones seem to contain information not present in the other variables. MaxEnt computes the area under the receiver's operating curve (AUC) to evaluate model performance. AUC values can range between 0.5 and 1.0, with 0.5 indicating that the model is no better than a random prediction. Values below 0.7 are considered low, those between 0.7 and 0.8 are considered good, and values greater than 0.9 indicate high discrimination, signifying that the model outperforms random predictions. However, it should be noted that AUC may not provide sufficient

information for assessing SDM performance. Therefore, in this study, an additional evaluation of the model was carried out using True Skill Statistic (TSS), which has been theoretically and empirically shown to be superior to both AUC and Kappa Statistic for measuring the performance of species distribution models (Allouche et al. 2006). The ASCII file containing possible habitat suitability was imported into ArcGIS 10.5 software, with predefined RCP (2.6, 4.5, 6.0, and 8.5). Subsequently, further analysis was conducted to investigate the direction of distribution of *C. junghuhniana* and *C. equisetifolia*, comparing existing data with potential future scenarios.

RESULTS AND DISCUSSION

Variable contribution and model evaluation

This study utilized multiple variables to determine their influence on the distribution area, affecting the results. The variables utilized in this study include pH (soil pH), elev (elevation), soc (soil organic carbon), uvb1 (Annual Mean UVB), uvb2 (UVB seasonality), uvb3 (Mean UVB of the lightest month), uvb4 (Mean UVB of the lowest month), bio 4 (Temperature seasonality), bio 5 (Maximum temperature of the warmest month), bio 8 (Mean temperature of wettest quarter), bio 9 (Mean temperature of the driest quarter), bio 10 (Mean temperature of the warmest quarter), and bio 11 (Mean temperature of the coldest quarter). The contribution percentage of each variable to the final model is presented in Table 2. For *C. junghuhniana*, the most influential variable was bio 10, accounting for 42.1% contribution to the modeling process. Bio 10 signifies a warm quarter, which aligns with the habitat of mountain fir, typically found in mountainous areas with not too cold and not too hot conditions. The second most influential variable was bio 4, contributing 18.3%. Bio 4, indicates that the plant can only grow and develop within a specific temperature range, highlighting its sensitivity to temperature conditions. The third most influential variable was bio 8, contributing 12% to the model. Bio 8 suggests that moisture is a crucial factor for the plant's survival. pH values account for 9.9%, elevation with 7.3%, while other variables contributed less than 5%. In contrast, for *C. equisetifolia*, the dominant variable affecting the results was the elevation, which contributed 25.2% to the model. This implies that *C. equisetifolia* is primarily found at specific altitudinal ranges. The second most influential variable was Bio 4, with a contribution of 19.8%, indicating the plant's preference for certain temperature conditions. pH variable accounting for 16.8%, represent the third most influential variable, signifying the plant's need for a particular level of acidity for growth and development. Other variables include bio 5 (10.8%), bio 9 (6.6%), uvb3 (6.5%), uvb2 (5.1%), and others contributing less than 5%. These variables represent the criteria essential for optimal growth and development of the two species. The jackknife data obtained from the MaxEnt analysis, as depicted in Figures 2 and 3, assigns distinct importance to *C. junghuhniana*. The most substantial variable influence can be observed in the variable bio 10;

while the least influential variables for this species were uvb1 and uvb3. Conversely, for *C. equisetifolia*, the most significant variable influence was found in bio 11, with uvb3 being the least influential among the variables. This comprehensive assessment of variables provided valuable insights into the habitat preferences and requirements of these two species, aiding in understanding their distribution patterns.

Table 2. Variable contribution percentage to the final model

Variables	Description	Contribution (%)	
		C. junghuhniana	*C. equisetifolia*
Elev	Altitude	7.3	25.2
bio_4	Annual Mean Temperature	18.3	19.8
bio_5	Maximum temperature of wettest quarter	1.2	10.8
bio_8	Mean temperature of wetteat quarter	12	1.4
bio_9	The mean temperature of the driest quarter	0.5	6.6
bio_10	The mean temperature of the warmest quarter	42.1	0.2
bio_11	The mean temperature of the coldest quarter	0	0.6
soil_carbon	Soil Organic Carbon	1.9	3.7
soil_ph	Soil pH	9.9	16.8
UVB1	Annual Mean UVB	0.6	2.1
UVB2	UVB Seasonality	4.6	5.1
UVB3	Mean UVB of Lightest Month	0	6.5
UVB4	Mean UVB of Lowest Month	1.5	1.2
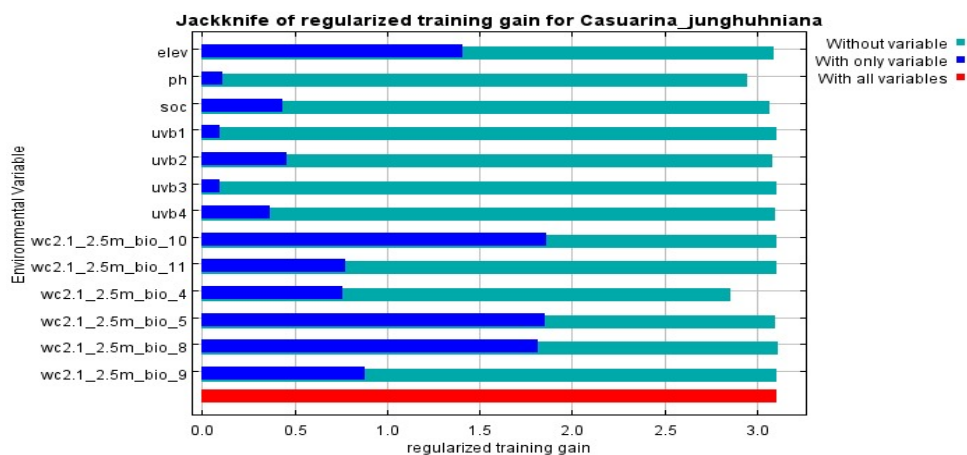
Figure 2. Jackknife test results are relatively important of the predictor variables for *Casuarina junghuhniana*
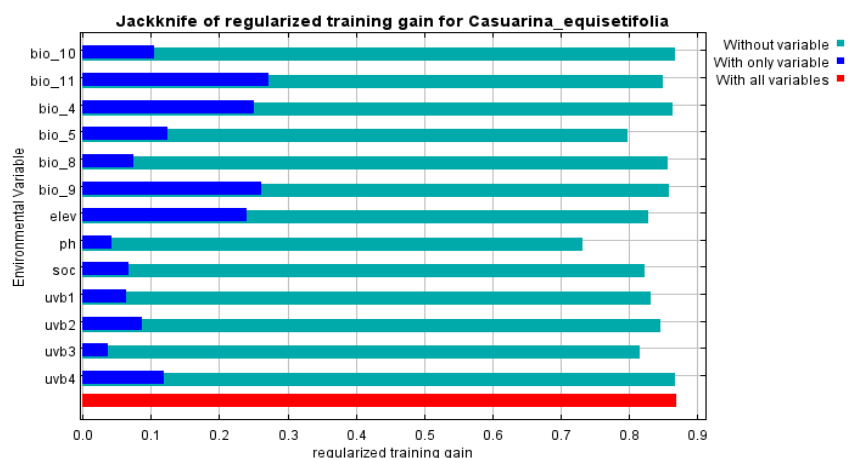
Figure 3. Jackknife test results are relatively important of the predictor variables for *Casuarina equisetifolia*

Prediction of current potential habitat distribution

In this study, models were created using 261 unique occurrence records of C. *equisetifolia* and 38 unique occurrence records of *C. junghuhniana* in Southeast Asia, derived from both primary and secondary sources. To determine the potential distribution of suitable habitats for now, as illustrated in Figure 5. Based on these findings, for *C. junghuhniana*, the current model predicted about 2.01% (320.21 km^2) of suitable habitats in East Timor. In addition , the model also predicted suitable habitats in Vietnam, accounting for around 0.33% (1106.66 km^2) of the total area, 0.16% (482.83 km^2) in the Philippines, 0.04% (138.51 km^2) in Malaysia, and 1.50% (30376.68 km^2) in Indonesia. Based on the results of the model, some countries in Southeast Asia, such as Thailand, Singapore, Myanmar, Laos, Cambodia, and Brunei Darussalam, do not possess suitable distribution areas for *C. junghuhniana*. Based on Figure 4, suitable habitat for *C. junghuhniana* in Indonesia was estimated to be evenly distributed in the central part of Java Island, the central part of Sulawesi Island, and the southern part of Papua. In addition, *C. junghuhniana* was also predicted to have suitable habitats in southern Vietnam, the central part of East Timor, Malaysia, and the Philippines.

Meanwhile, it was predicted that approximately 60.81% (430.30 km^2) of Singapore's habitat was suitable for *C. equisetifolia*. Furthermore, the model predicted approximately 51.42% (158717.67 km^2) of suitable *C. equisetifolia* habitat was present in the Philippines, 27.40% (1588.78 km^2) in Brunei Darussalam, 15.75% (2510.32 km^2) in East Timor, 15.71% (52031.65 km^2) in Vietnam, 21.70% (7243.70 km^2) in Malaysia, 4.95% (26182.13 km^2) in Thailand, 9.89% (18157 km^2) in Cambodia, 6.17% (124908.33 km^2) in Indonesia, 1.14% (8041.55 km^2) in Myanmar, and 0.31% (712.19 km^2) in Laos. As depicted in Figure 4, suitable habitats for *C. equisetifolia* were estimated to be evenly distributed along the southern coast of Vietnam, Thailand, and Malaysia. In Indonesia, the model suggests suitable habitats in the south and along the northern coastal area of Kalimantan Island, the northern coastal region of Java Island, both the northern and southern coastal areas of Sumatra Island, the southern coastal areas of Sulawesi Island, and the northern and southern coastal regions of Papua. Furthermore, the central part of the Philippines was also found to be suitable for *C. equisetifolia*.

Potential future changes in the distribution of suitable habitats

Predictions regarding the potential impact of climate change on the redistribution of suitable habitats for *C. junghuhniana* and *C. equisetifolia* are shown in Figure 4. Future model scenarios reveal substantial declines in climate-suitable habitats for both species across all scenarios in 2030, 2050, and 2080. In 2030, as per the model utilizing RCP 2.6, characterized by low Green
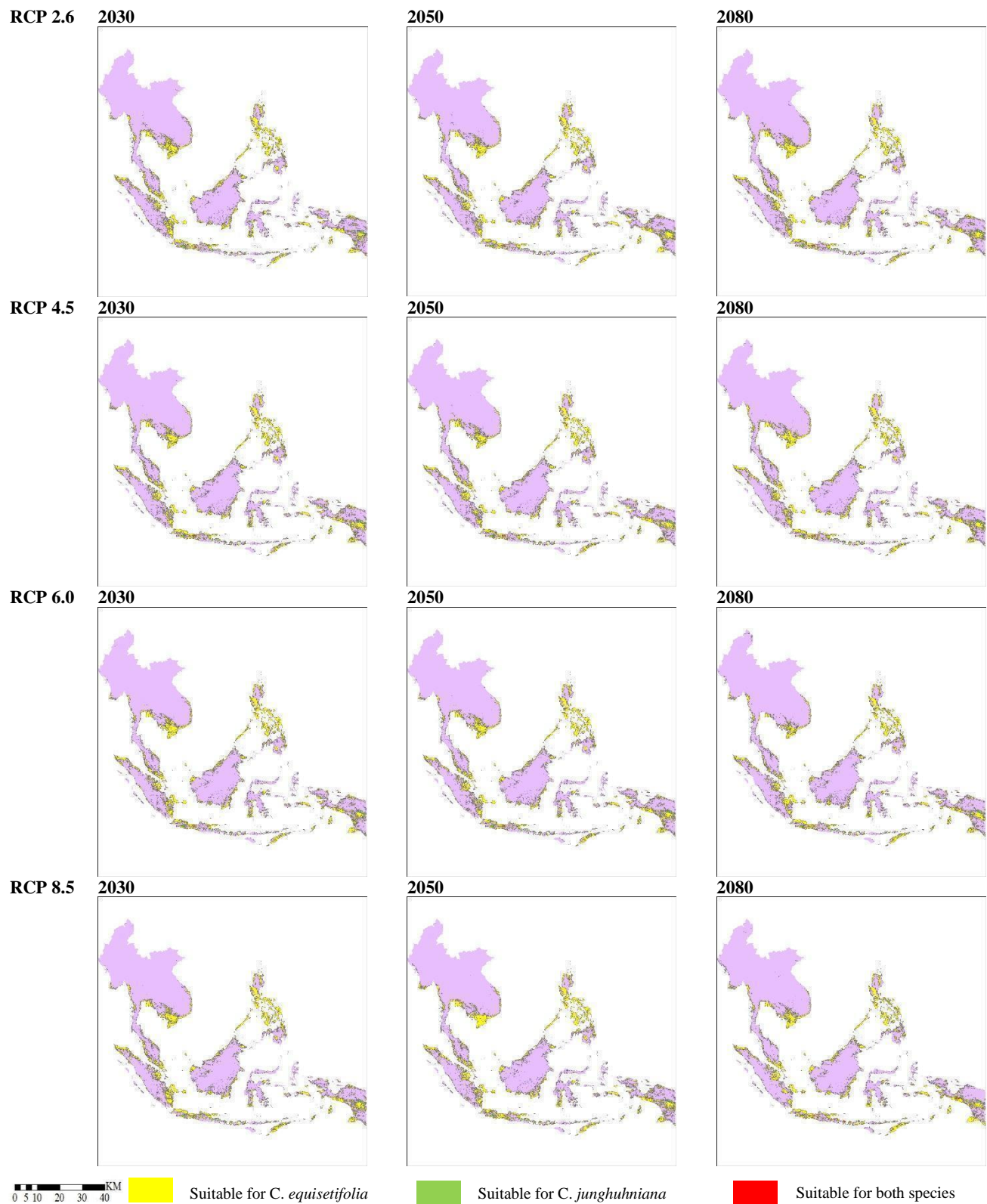
House Gas (GHG) emissions, the habitat area for *C. equisetifolia* is projected to increase by 3% under the influence of climate scenarios. Simultaneously, the habitat area of *C. junghuhniana* is expected to increase by about 0.04%. However, the number of suitable habitats for both species is expected to decrease by a greater percentage than the predicted increase in habitat. In 2050 and 2080, the model indicates a decrease in total suitable habitat for *C. equisetifolia* of about 3% in each period.

Meanwhile, *C. junghuhniana* is predicted to decrease in total area by 19% in 2030 and 26% in 2050. The areas suitable for *C. equisetifolia* that are expected to decrease are primarily located in the southern regions of Sumatra Island, Indonesia, the northern part of the Philippines, and the central part of East Timor. In contrast, changes in *C. junghuhniana* in some areas of the country did not show significant changes (Table 3, Figure 4).

Under RCP 4.5, the model estimates a decline in the suitable area for *C. equisetifolia* by 11-16%. Simultaneously, the suitable area for *C. junghuhniana* is projected to decrease by approximately 21-23% in 2030, 2050, and 2080. According to the model, by 2050, suitable areas for *C. equisetifolia* will decrease, primarily in southern Thailand and northern Peninsular Malaysia. In 2080, range of *C. junghuhniana* is anticipated to decrease in the northern region of the Philippines, while *C. equisetifolia* has been projected to face decline in the eastern region of Sumatra Island, Indonesia (Table 3, Figure 4).

Under RCP 6.0, MaxEnt projects a higher decline in the suitable area for *C. junghuhniana* by 2030 compared to the previous RCP, ranging from 0.01-0.03%. At the same time, the suitable area of *C. equisetifolia* is anticipated to decrease by about 4-11% between 2030, 2050, and 2080. Significant declines in the corresponding area for *C. equisetifolia* are projected in southern Vietnam, southern Peninsular Malaysia, eastern Sumatra, western Java, southern Kalimantan, Papua, and central East Timor. *C. junghuhniana* is expected to undergo significant changes in the central part of Java, Indonesia (Table 3, Figure 4)

On the RCP 8.5 trajectory in 2050, the largest decrease in the suitable area for *C. equisetifolia* was observed compared to the previous RCP scenarious, with an 18%. When considering the three timeframes (i.e. 2030, 2050, and 2080), the suitable area for *C. equisetifolia* has decreased by around 11-18%. Meanwhile, the area for *C. junghuhniana*, has decreased by the range of about 16-20% in the same time frames (Table 3). Based on Figure 4, significant changes in the suitable area for *C. equisetifolia* are expected in the southern regions of Borneo, Sulawesi, Papua, and the central part of Sumatra Island, Indonesia, central Peninsular Malaysia, southern Philippines, and northern Brunei Darussalam. For *C. junghuhniana*, the change in area was predicted to be mainly in the southern region of Sulawesi Island, Indonesia.

RCP 2.6 **2030**   **2050**   **2080**

RCP 4.5 **2030**   **2050**   **2080**

RCP 6.0 **2030**   **2050**   **2080**

RCP 8.5 **2030**   **2050**   **2080**

KM
0 5 10   20   30   40   Suitable for C. *equisetifolia*   Suitable for C. *junghuhniana*   Suitable for both species

Figure 4. Redistribution of climate-suitable habitats under projections of future climate

Table 3. Dynamics of habitat area change are appropriate for *Casuarina junghuhniana* and *C. equisetifolia* under four combinations of future climate scenarios in three different periods

Years	RCP Projection	*C. junghuhniana* (Area × 10³ km²)				*C. equisetifolia* (Area × 10³ km²)			
		Loss	Gain	Total	Future	Loss	Gain	Total	Future
2030	RCP 2.6	5,629.5 (19%)	1,822.5 (0.04%)	3,807	4,140,113	-8,430 (-13%)	91,752.75 (-3%)	-100,183	3,425,672
	RCP 4.5	6,925.5 (21%)	526.5 (0.01%)	6,399	4,139,586	-71,746 (-11%)	79,197.75 (-2%)	-150,944	3,438,227
	RCP 6.0	7,188.75 (24%)	2,63.25 (0.01%)	6,925.5	4,139,849.3	-74,601 (-11%)	82,053 (-2%)	-156,654	3,435,372
	RCP 8.5	6,115.5 (20%)	1,336.5 (5.45%)	4,779	4,138,776	-91,955 (-14%)	99,407.25 (-3%)	-191,363	3,418,018
2050	RCP 2.6	5,771.25 (19%)	1,680.75 (0.04%)	4,090.5	4,138,290	-96,633 (16%)	104,085 (-3%)	-200,718	3,413,340
	RCP 4.5	6,257.25 (21%)	1,194.7 (3.97%)	5,062.5	4,138,917.8	-68,607 (-11%)	76,059 (-2%)	-144,666	3,441,366
	RCP 6.0	6,176.25 (20%)	1,275.75 (0.03%)	4,900.5	4,138,836.8	-64,861 (-10%)	72,312.75 (-2%)	-137,174	3,445,112
	RCP 8.5	5,001.75 (17%)	2,450.25 (0.06%)	2,551.5	4,137,662.3	-115,830 (-18%)	123,201 (-4%)	-239,031	3,394,224
2080	RCP 2.6	7,776 (26%)	-324 (-0.01%)	8,100	4,140,436.5	-85,860 (-13%)	93,312 (-3%)	-179,172	3,424,113
	RCP 4.5	6,925.5 (23%)	526.5 (0.01%)	6,399	4,139,586	-102,263 (16%)	109,714.5 (-3%)	-211,977	3,407,711
	RCP 6.0	6,581.25 (22%)	870.75 (0.02%)	5,710.5	4,139,241.8	-25,495 (-4%)	32,946.75 (-1%)	-58,441.5	3,484,478
	RCP 8.5	4,799.25 (16%)	2,652.75 (0,06%)	2,146.5	4,137,459.8	-70,997 (-11%)	78,448.5 (-2%)	-149,445	3,484,478

Core distribution shift

Assessment of the core distribution shift in *C. equisetifolia* revealed migration from Indonesian-Malaysian border in Borneo southeastwards to Indonesian Borneo (Kalimantan), while *C. junghuhniana* shifted eastward from the Gulf of Bone to east of Sulawesi. Under current climatic conditions, approximately 652,819 km² (15.65%) of suitable habitat exists for *C. equisetifolia*, and 30,132 km² (0.7%) of *C. junghuhniana*. However, the habitat of *C. junghuhniana* is expected to gradually diminish due to future climate change, resulting in declining population and distribution. By 2080, the total habitat area for *C. junghuhniana* is projected to decrease by a mere 25,332 km² (0.6%). In contrast, the habitat area for *C. equisetifolia* is predicted to expand to 755,082 km² (18%). This increase may be attributed to the species's resilience to future climate change. In addition, the anticipated redistribution of supportive habitats for both species under future climate conditions will also change their core geometric distribution. Presently, suitable habitat for *C. equisetifolia* is concentrated along Malaysia's border with Indonesia. However, in the coming years, the habitat is expected to shift towards Indonesian Borneo. The centroid of suitable habitat is currently located at 115°14'34.649"E and 3°29'58.457"N in Malaysia (Figure 5). Under RCP 2.6, the corresponding centroid is projected to shift slightly towards southeast to 115°44'33.765"E, 2°57'40.116"N. Shifts under RCP 4.5, RCP 6.0, and RCP 8.5 indicate a modest eastward expansion, then ranging from 0.75 km to 0.78 km eastward at 115°50'8.314"E 2°56'9.353"N, under RCP 4.5. Subsequently, it is projected to shift 1.46 km southeastward at 116°22'6.941"E, 2°33'47.656"N under RCP 6.0, and further to 1.58 km southeastward at 116°20'59.856"E, 2°32'53.988"N under RCP 8.5.

Furthermore, concerning the shift in the habitat center of *C. junghuhniana*, modest shifts were observed RCP 2.6, RCP 4.5, and RCP 6.0, whereas a substantial shift was projected under RCP 8.5. The current distribution of suitable habitat for *C. junghuhniana* is around the Gulf of Bone at 121°27'8,532"E and 5°4'29,426"S. However, in the near future, it is expected to shift towards Southeast Sulawesi. Under RCP 8.5, centroids are predicted to shift eastward by 4.2 km to 125°39'45.433"E, 4°57'31.716"S. Shifts under RCP 2.6 extend up to 1.5 km at 122°57'38.76"E, 5°23'43.101"S, while under RCP 4.5, they are expected to reach 1.2 km at 122°43'43.34"E, 5°9'47.681"S. Finally, shifts under RCP 6.0 span as far as 2.2 km, situated at 123°40'44.583"E, 4°49'34.333"S. Overall, it was observed that there was eastward shift across all RCP scenarios.
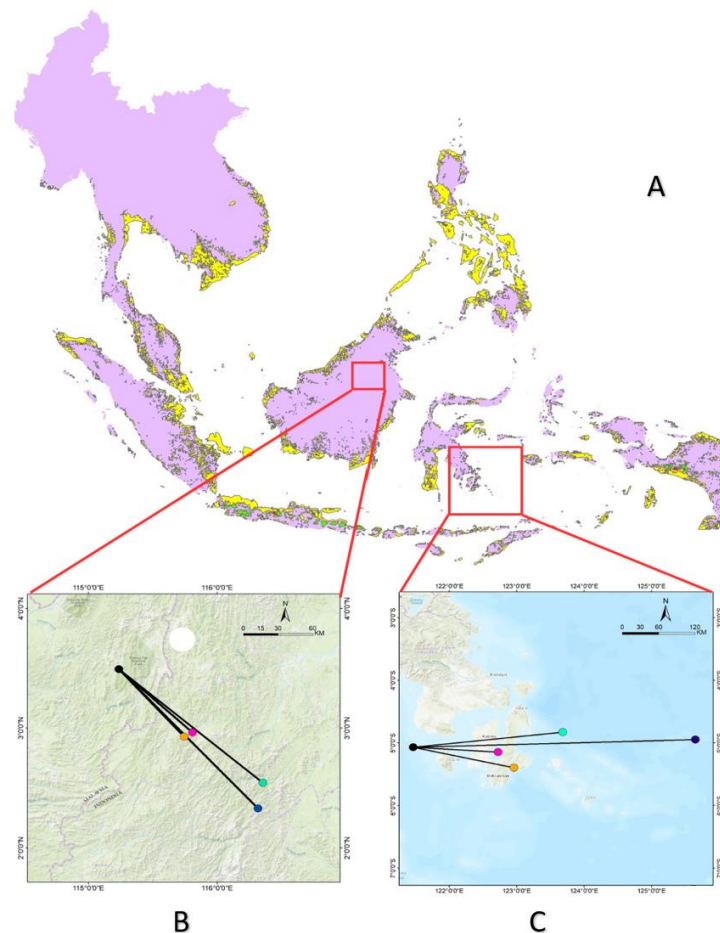
Figure 5. A. Prediction of the potential distribution of *Casuarina equisetifolia* and *C. junghuhniana* under current climatic conditions. Core distribution shifts in climate scenarios by 2080; B. *C. equisetifolia* and C. *C. junghuhniana*. Black dot indicates the geometric center of suitable area under current climate conditions (●). Colored dots indicate the new geometric centers (● RCP 8.5, ● RCP 6.0, ● RCP 4.5, ● RCP 2.6). The arrows depicting magnitude and direction of predicted change

Discussion

Research related to *C. equisetifolia* and *C. junghuhniana* has been extensive; however, there has been a notable absence of predictions concerning their future habitat distribution in response to climate change. Understanding how climate change impacts habitat distribution is crucial for assessing and predicting the habitat distribution of *C. equisetifolia* and *C. junghuhniana*. As depicted in Figure 4, *C. equisetifolia* appears to have an optimal fit within the environments along the southern coast of Vietnam, Myanmar, Thailand, Singapore, and Malaysia. The study highlights Singapore as having the largest percentage of suitable habitat area for *C. equisetifolia*, encompassing 60% of the total area. It is crucial to properly manage this habitat, considering the significant ecological role of *C. equisetifolia*, such as its ability to restore and enhance the ecological functions of sandy areas. Appropriate management, including soil fertility improvement through amelioration (Nugroho and Sumardi 2010), is advisable due to *C. equisetifolia*'s sensitivity to drought and exposure to sea breezes. In Indonesia, suitable habitats for *C. equisetifolia* are projected to include the southern and northern coastal regions of Kalimantan, Sumatra, and Papua, as well as the northern coast of Java and southern coast of Sulawesi. Similarly, *C. junghuhniana* is predicted to have suitable distribution areas in the central regions of Java, Sulawesi, the Lesser Sunda Islands and the southern part of Papua (Indonesia). Additionally, *C. junghuhniana* is anticipated to find suitable habitats in southern Vietnam, the central part of East Timor, Malaysia, and the Philippines (Figure 4). It is noteworthy that the limited availability of data on *C. junghuhniana* in GBIF has contributed to the relatively small quantum of suitable habitat in Southeast Asia.

Like other plant species, *C. equisetifolia* and *C. junghuhniana* are influenced by factors such as temperature, water availability, UVB radiation intensity, which affect photosynthetic activity and plant defense mechanisms (Battaglia et al. 2000; Márquez-Escalante et al. 2006), increased CO_2, and nutrient availability (Wu et al. 2009). Temperature seasonality (bio 4) quantifies temperature fluctuations throughout the year (O'Donnell and Ignizio 2012) and can significantly impact photosynthetic activity. Moreover, annual rainfall, representing water availability, plays a pivotal role in shaping the distribution of both species. Ruszala et al.

(2011) explained that water availability is related to many environmental factors, such as plants' biochemical and physiological processes. Hydrothermal conditions indirectly shape the ecology and distribution patterns of these species. *C. equisetifolia*, in particular, displays robust adaptability to coastal conditions, thriving in environments characterized by drought, high temperatures, abundant sunlight, strong winds, and high salt levels (Rahayu et al. 2016). Moreover, it has been observed that *C. equisetifolia* can successfully compete with other species, such as *Ipomoea pes-caprae* (Wardhani and Poedjiraharjoe 2020).

Due to anticipated impacts of future climate change on Southeast Asia, the habitat distribution of both *C. junghuhniana* and *C. equisetifolia* is projected to undergo significant alternations in their geographical distribution patterns. Projections suggest changes in habitat suitability, with both increases and decreases suitable habitat areas. Under lower and moderate GHG emission projections (RCP 2.6, RCP 4.5, RCP 6.0), radiation forcing is predicted to gradually increase before stabilizing by 2100 (IPCC 2014). Simultaneously, average annual temperatures are projected to rise by 1.7-5°C across Southeast Asia. However, changes in rainfall patterns will vary across sea areas, with some regions experiencing up to 15% more rainfall than current levels, particularly in the Northern Philippines, Myanmar, and Laos (IPCC 2014). These conditions will drive alterations in suitable habitat distribution for both species, even resulting in a reduction in supporting habitat for *C. junghuhniana*.

The maps presented in this study illustrate predictions of habitat distribution that support the existence of both species. These predictions are based climate, topography, edaphic, and UVB radiation variables. Nonetheless, it's important to note that while these models offer valuable insights, they do not represent definitive or absolute habitats. Several factors can influence the accuracy of habitat distribution predictions, including limited availability of data, microclimate variations, and the effects of anthropogenic activities like land use changes, deforestation, and pollution (Fontúrbel et al. 2015). Omission errors can also occur due to incomplete event data used in the models (Setyawan et al. 2018). Despite these limitations, this study provides a foundational understanding of how current climate conditions impact the distribution of suitable habitats for *C. junghuhniana* and *C. equisetifolia*, and offers predictions for their redistribution under future climate change scenarios.

Creating an ideal model requires substantial high-quality data. Limitations in the availability of ecological and physiological data can impact model accuracy (Setyawan et al. 2018). Nevertheless, as climate models improve, there is an opportunity to develop more precise and ideal models. Despite the current limitations, this study serves as a basis for understanding the potential consequences of climate change on the predicted distribution of suitable habitats for *C. junghuhniana* and *C. equisetifolia*. These projections demonstrate how these species may experience changes in their extent of suitable habitat distribution and shifts in their distribution patterns due to future climatic conditions. Initially, the habitat

distribution comprised only 652,819 km^2 (15.65%) for *C. equisetifolia* and 30,132 km^2 (0.7%) for *C. junghuhniana*. By 2080, under RCP 4.5, *C. equisetifolia*'s habitat area expanded to 755,082 km^2 (18%), while *C. junghuhniana*'s habitat area decreased to 25,332 km^2 (0.6%) in RCP 8.5. *C. equisetifolia*'s core distribution shifted from the Malaysian-Indonesian border in Borneo towards the southeast, while *C. junghuhniana*'s core distribution shifted from the Gulf of Bone towards the east of Sulawesi.

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