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continued on the back inside cover

Cover: Illuminating the cruelty of Pangolin trade in India for the purpose of black magic, for the sanctity of protection. Using an animal's shell, ripping its armor against the world to protect oneself. When does one become the evil they are trying to ward off? — Acrylic on wood. © Maya Santhanakrishnan.

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ARTICLE

Distribution and habitat suitability of *Amorphophallus gigas* with MaxEnt modeling in north Sumatra, Indonesia

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Abstract: *Amorphophallus gigas* is exclusively found in community agroforestry gardens within the northern Sumatra region, Indonesia. This species faces various threats including land conversion and tuber extraction for economic purposes. Despite its unique habitat characteristics, the conservation status remains unrecorded on the IUCN Red List. Effective conservation requires comprehensive data, including distribution and habitat conditions in the field. Therefore, this study aimed to analyze the variables affecting the distribution of *A. gigas* in northern Sumatra and predict the size of the area with the potential for spread. The variables examined included height, slope, slope direction, climatic conditions, and land cover. Coordinate points were taken directly in the field using GPS, while Maximum Entropy (MaxEnt) modeling was used to predict the suitability of the habitat of the species. MaxEnt modeling of variables affecting the distribution of *A. gigas* showed that soil type played an important role (contribution 55%), followed by the average monthly temperature range (16%), and altitude (7.9%). The most suitable area was found to be located in the southern part of the province. The results of this research are useful for formulating conservation strategies for *A. gigas*.

Keywords: Alismatales, altitude, Araceae, conservation strategy, corpse flower, distribution modelling, monthly temperature, population ecology, soil type, spatial ecology.

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INTRODUCTION

The Indonesian flora is part of the Malesian flora, renowned for its rich biodiversity (Latifah et al. 2021). The Malesian region covers Indonesia, Malaysia, the Philippines, Papua New Guinea, and parts of Thailand and southeastern Asia. A prominent plant family within this region is Araceae, which includes the genus *Amorphophallus* (Van et al. 2020). Northern Sumatra Province, covering an estimated forest area of ±3,010,160.89 ha (approximately ± 41.25% of the total land area), hosts diverse flora and fauna, including *Amorphophallus* species. With over 200 species distributed from western Africa to tropical Asia and northern Australia, these plants are notable for their large size and the foul odor emitted during flowering, resembling decaying animals (Shirasu et al. 2017; Yuzammi et al. 2018).

Several species of *Amorphophallus* hold economic value and are cultivated in tropical and subtropical regions worldwide (Mutaqin et al. 2020). These species contribute quite significantly to food security due to their high glucomannan content, a polysaccharide widely used in the food, pharmaceutical, and chemical industries (An et al. 2010; Chua et al. 2010). Historically, the tubers and flowers of *Amorphophallus* have been utilized as food and medicine for over 2,000 years ago by the ancient southeastern Chinese people (Handayani et al. 2020). In northern Sumatra, the tubers were harvested primarily for their economic value rather than for direct consumption or medicinal use. I In regions such as Java, *Amorphophallus* was incorporated into the diet (Mutaqin et al. 2020; Widyastuti et al. 2020) and used to treat diabetes (Sutriningsih & Ariani 2017). Similarly, in East Nusa Tenggara, the shoots and leaves of *Amorphophallus muellerii* are consumed and used for medicinal purposes, including stimulating breastmilk production and as an astringent and analgesic (Santosa & Sugiyama 2016).

In Indonesia, 25 *Amorphophallus* species have been identified, including the iconic *Amorphophallus titanum* (Becc.), listed in the IUCN Red List (Yuzammi et al. 2018), and *Amorphophallus gigas* Teijsm. & Binn., naturally occurring in agroforestry areas in northern Sumatra (Rambey et al. 2021, 2022). Despite the ecological and economic importance, *Amorphophallus* species remain underexplored in northern Sumatra. These species play vital roles in biodiversity maintenance and nutrient cycling within forest ecosystems (Singh & Gadgil 1995; Wahidah et al. 2022). Threats such as land conversion for agriculture and human activities pose serious risks to their survival. *A. titanum*, as one of the largest inflorescences in the world, is vulnerable due to its restricted distribution and long maturation period. Public awareness of the conservation status and ecological significance of these species remains low, further jeopardizing their preservation (Yudaputra et al. 2022). Although *A. gigas* has not been officially classified as a protected species, the plant is rarely documented when it blooms in fields or forests. The habitat of the species is also at risk of degradation or loss due to its coexistence with agroforestry practices or human interference.

Conservation of *Amorphophallus* species has been prioritized through the strategic action plan spanning from 2015 to 2025 (Yuzammi et al. 2015). One important aspect to support conservation efforts is a systematic assessment of *A. gigas* populations in the wild, specifically in habitats that are in contact with human activities. It is important to understand that not all human activities directly inhibit growth and endanger the conservation status of this species. In the field, the reality is that complex agroforestry planting patterns serve as a harmonious strategy crucial for protecting and sustainably using *A. gigas*. Previous studies have reported the potential of wild cultivation and utilization of *Amorphophallus* spp. as edible crops and ethnomedicinal materials in northern Sumatra (Rambey et al. 2022a). This is evident in the discovery of various species growing around forests and agroforestry land, including *Amorphophallus gigas*, *Amorphophallus titanum, Amorphophallus paeoniifolius*, *Amorphophallus prainii*, and *Amorphophallus beccarii* (Supriati 2016). Based on initial surveys, data collected from 2019 to 2021 indicate substantial exploitation of *A. gigas* and *A. titanum* in the field, primarily for export purposes. In Sumatra, the population of *A. titanum* has declined significantly due to overharvesting of its tubers (Yudaputra et al. 2022). In 2018, exports of *Amorphophallus* tubers amounted to 254 t, generating IDR 11.3 billion, and were shipped to countries including Japan, Vietnam, China, and Australia, among others (Utami 2021). Given the scarcity of information regarding the habitat suitability for *A. gigas*, it is essential to assess whether natural populations of this species are still conserved.

The habitat suitability of *A. gigas* was modelled in this study using ecological niche modeling with Maximum Entropy (MaxEnt). This method aims to evaluate and predict habitats or areas with the potential to become distribution locations that meet the growth requirements for this species (Saputra & Lee 2021). In the data analysis process, MaxEnt requires various data sets representing the location of species occurrences and environmental information (Phillips & Dudík 2008). Environmental data included six variables: distance from roads, distance from rivers, slope, altitude, topography, and annual bioclimate. These variables were chosen for their known influence on habitat suitability and species distribution, providing insight into how landscape and climate affect *Amorphophallus* populations, particularly in areas facing land conversion (Rahman et al. 2019). Suitability of land use is used as a basis for planning and decision making in rational land management. In several studies, geographic information systems (GIS) have been commonly used to analyze land suitability (Rahmawaty et al. 2020). Investigations into the land suitability of *Amorphophallus* have been undertaken by both Wahyu et al. (2022) and Komsiati & Achyani (2021). The identified locations of *A. gigas* were found on slopes ranging between 30% and 60%, classifying them under the steep terrain category. Effective management strategies must prioritize conservation while allowing sustainable use, ensuring biodiversity and long-term availability of this valuable genus. Despite the presence of *Amorphophallus* species in northern Sumatra, including *A. gigas*, research on their distribution remains limited. This study aims to fill this gap by using MaxEnt to evaluate habitat suitability, providing a foundation for future conservation initiatives.

METHODS

Study Area

This study was conducted in 2023 in north Sumatra, including southern Labuhanbatu, northern Padang Lawas, southern Tapanuli, northern Tapanuli, and Mandailing Natal Regency. Northern Sumatra is located between 0.568–4.305 N and 97.059–100.424 E (Figure 1). According to climatic data provided by Statistics Indonesia of northern Sumatra (https://sumut.bps.go.id/) in 2023, temperatures in the region fluctuate between 13.4°C and 33.9°C, with humidity ranging from 78% to 91%. Annual precipitation varies between approximately 800 mm and 4,000 mm. Over the past five years, observable climate change phenomena in northern Sumatra include a documented increase in temperature and erratic precipitation patterns. Northern Sumatra's land cover shows that most of the area is dominated by forest cover and agroforestry area. The point sample of species locations was found in community agroforestry areas for rubber, durian, and cacao. Agroforestry in almost all regions had a complex pattern resembling a forest. *Amorphophallus gigas* in northern Sumatra is found at an altitude of 40 to 950 m. The survey of *Amorphophallus* was conducted in all forest locations, both natural forests and agroforestry areas. In the Northern Padang Lawas District, *Amorphophallus gigas* was found at the edges of the Barisan Hills forest at various elevations. In the southern Tapanuli District, *Amorphophallus* was located in agroforestry gardens adjacent to natural forests. In both the southern Tapanuli and northern Tapanuli Districts, *Amorphophallus* coexists with natural forests. The exploratory findings revealed that the distribution of *A. gigas* in southern Tapanuli and northern Tapanuli is at elevations below 1,000 m, which are predominantly agroforestry lands owned by the community. Elevations above 1,000 m are natural forests managed by the government's conservation agency, the Natural Resources Conservation Agency. Surveys in the natural forests of southern Tapanuli and northern Tapanuli Districts at elevations above 1,000 m revealed a different species, *Amorphophallus beccarii*. In the Mandailing Natal District, *A. gigas* was found in limited production forests that are adjacent to natural forests.

Data Collection

The materials used were thematic maps including topography, land cover, climate, soil types, roads, rivers, and villages, as well as community socio-economic data. These data were chosen due to the high contribution of each variable (altitude, slope aspect, distance from river, distance from road, and 19 bioclimates) to the species distribution in the model after the first running of the MaxEnt model. Distance from road indicates the potential of human activity to this species' potential distribution, while distance from river shows the correlation between water bodies to the species' location to distribution across the area. For image processing and analysis, a licensed ArcMap 10.8, DivaGIS version 7.5.0, JavaScript, and MaxEnt application version 3.4.1 are available in the Universitas Sumatra Utara.

Several steps were undertaken to predict the distribution of *A. gigas*, including the collection of primary and secondary data. Primary data were collected through field observations using purposive sampling, where sample locations were identified by local communities or through direct findings in the field. Distribution data were recorded using a Global Positioning System (GPS) across various regions in northern Sumatra. After confirming the presence of *A. gigas*, the geographic coordinates were recorded. A total of 34 point locations were included in the MaxEnt analysis, with 24 points used for training and 10 points

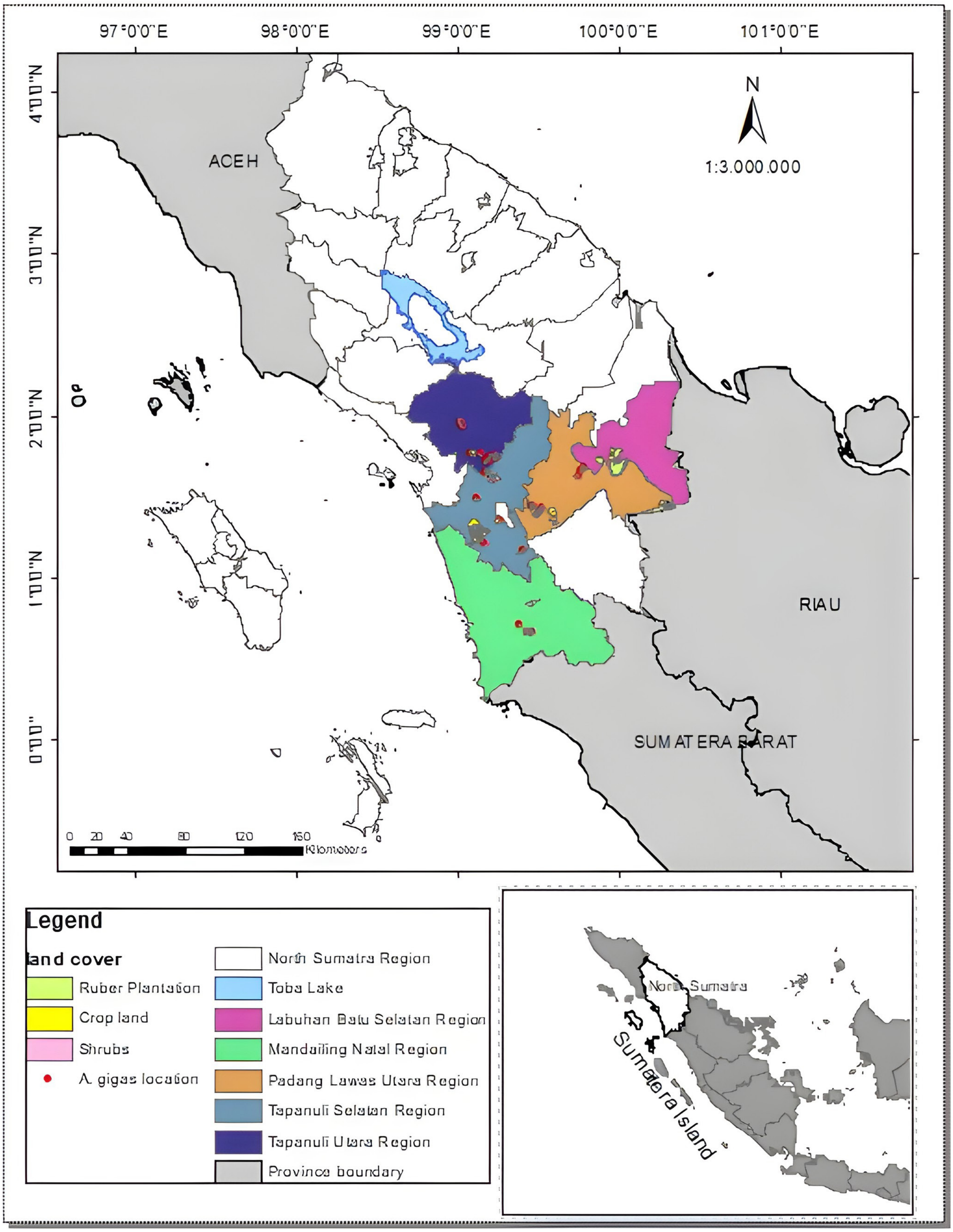

Figure 1. Map showing study sites, distribution coverage, and land cover of *Amorphophallus gigas* habitats.

for testing.

Secondary data supporting this study included information on topography, slope, elevation, soil type, and land cover obtained from DEMNAS (Indonesian Geospatial Portal). Additional data, such as area boundary shapefiles, road networks, and river networks, were sourced from geospatial websites. Bioclimatic and geospatial data from BIG (Indonesia) were acquired from the WorldClim.org website, along with general information about the study area's conditions. Table 1 provides an overview of the data, sources, and types in this study.

Construction of Environmental Variables Mapping

Maps of road and river distances in this study were processed using ArcGIS 10.8 and distance analysis was carried out with the Euclidean distance method in the Arc ToolBox ArcGIS option. Distance map data from roads and rivers were downloaded from the Indonesian Earth Rupa map in shapefile form on the INA Geospatial Portal. The road and river distance maps were created from the road and river networks respectively in the northern Sumatra Province region. Altitudinal class maps were created with DEMNAS data using the ArcGIS 10.8 application.

Height map data was downloaded in grid form, and the digital elevation model (DEM) data obtained from the DEMNAS Indonesia Geospatial Portal was adjusted to the study location. The conversion of vector data to raster form was carried out by equalizing the resolution units of the extract by mask projection. Slope maps were created with a similar procedure for creating a height map. The analysis used a base elevation map, which was then processed in the Arc Toolbox to produce a percentile map projection. Class division referred to the decree issued by the director general of Watershed Management and Social Forestry regarding Technical Instructions for Compiling Critical Land Spatial Data, Number: P.4/v-set/2013.

Soil maps showed physical and chemical properties such as pH, texture, organic matter content, depth, etc. in line with the FAO (Food and Agriculture Organization of the United Nations) soil classification at a resolution of 30 m. The soil type data was obtained from the FAO Soil Classification portal dataset. These maps were generally used for agricultural purposes, environmental engineering, natural resource conservation, and land use planning. Soil maps usually include information such as soil type, depth, water capacity, organic matter content, soil structure, and nutrient content. This information can be used to understand the quality and land use method that best suits soil characteristics. The map was downloaded from the Indonesian Geospatial Portal website, and then the data were processed by adjusting to the study location.

All data were assimilated into the projection unit, and the extension was extracted with a mask in the raster. Interpretation of land cover/vegetation was divided into three main classifications, namely forest, no forest, and no data, each of which was further classified. The land cover classes included vegetative land (forest, plantations, shrubs, grass), open land, as well as settlements and water bodies (Saputra & Lee 2019). The 2019 land cover map data was obtained from the Indonesian Geospatial Portal website by downloading the overall land cover classification map file in the form of dry primary forest land, bushes, bare land, dry land secondary forest, regional industrial forest plantations (HTI), rice fields, primary mangrove and ancient swamp forests, swamp bushes/grass, settlements, agricultural land interspersed with shrubs, ponds, swamps, mangrove and swamp secondary forests. The data were then processed by cutting out the area required for the search.

Bioclimate data was obtained from the WorldClim website (https://www.worldclim.org/data/worldclim21.html), which provided 19 climate variables, including annual trends in the form of average temperature and rainfall, as well as seasonality namely coldest and hottest seasons or the wettest and driest. This variable explained the impact of climate on the distribution of species in spatial data (O'Donnell & Ignizio 2012). It is commonly used in HR analysis both for current and future distribution predictions. In MaxEnt analysis, a sample layer comprising discovery coordinates and an environmental layer in raster form including elevation, slope and terrain (aspect), soil type, distance from roads and rivers, land cover, and 19 bioclimatic variables (Fick 2017) were used with a spatial resolution of 30 arc s or the equivalent of around 1 km^2 (Hijmans et al. 2005).

The MaxEnt model estimates a target probability distribution by calculating the probability distribution of maximum entropy which makes it well-suited for species distribution modelling. The processed environmental data were collected and adjusted to the northern Sumatra region with the same resolution, area, and geographic coordinate system. The environment layer was converted into an Actionscript Communication (ASC) file implemented in MaxEnt analysis. For sample classes, the analysis used the CSV (Comma Separated Values) format. Subsequently, in the post-analysis process, the distribution analysis output of *A. gigas* was overlaid on the district administrative map. Figure 2 shows a flowchart illustrating the study procedure for analyzing the distribution and habitat suitability of *A. gigas* using MaxEnt and ArcMap tools.

Data Analysis

Amorphophallus gigas habitat suitability in this study was modelled using Ecological Niche Modeling with MaxEnt. This method aims to evaluate and predict the most suitable habitat in the study area. All environmental variables were combined with data points showing the presence of *A. gigas* and analyzed to determine the most influencing factors.

MaxEnt analyzed species presence data in the field directly in the form of historical data, and the probability of existence. Various areas with environmental information were examined, using a probability range of 0–1 with three observation samples including, environmental variables, future scenarios, and the extent of one suitability map (Saputra et al. 2019). The model used 10 replicates with one regularization multiplier and 30 % of random test data of *A. gigas* occurrence data. The model runs for 5,000 maximum iterations. The higher the number, the higher the chance of the species appearing. Probability numbers were classified into five groups. Areas with a probability greater than or equal to 0.4 were considered suitable and others unsuitable. Classification of habitat suitability of *A. gigas* with probability values is presented in Table 2.

The goal of MaxEnt is to estimate a target probability distribution by finding the maximum entropy probability distribution (Phillips et al. 2006). The perfect formula for Species Distribution Models with presence and absence data represented as follows (Phillips & Dudik 2008):

$$P(y = 1|x) = \frac{P(y = 1|x)\,P(y = 1)}{P(x)} \quad (1)$$

Where P (y = 1|x) is the probability of existence of the species at location x (y ranges from 0 to 1), P(x|y = 1) is the current observation or distribution realization in area x annotated as π (x) , P(y = 1) is the probability of presence, and P(x) = 1/|X| is the area-wide probability of location X. Similarly

$$P(y = 1|x) = \pi(x)\,P(y = 1)|X| \quad (2)$$

Where s

$$q_{\lambda}(x) = \frac{\exp(\sum_{i=1}^{n} \lambda j\, fj(x))}{Z\lambda} \quad (3)$$

Where qλ(x) is the MaxEnt distribution, $\exp(\sum_{i=1}^{n} \lambda j\, fj(x))$ is the exponential parameterized with feature vector (f) and (λ), and Zλ is a normalization constant that ensures the values of qλ(x) add up to unity over the entire area. The formula is calculated as follows:

$$H = \sum q\lambda(x) ln(q\lambda(x)) \quad (4)$$

Where H is the maximum entropy, and qλ(x) is the Maxent distribution from Equation (3). After obtaining an estimate of qλ, sufficient information is obtained to calculate the probability distribution P(y = 1|x), as shown by Equation (5)

$$P(y = 1|x) = \frac{e^{H} q_{\lambda}(x)}{1+e^{H} q_{\lambda}(x)} \quad (5)$$

Where qλ is the estimated probability of presence with maximum entropy π, and H is the entropy qλ.

The MaxEnt model was evaluated using the area under the curve (AUC), calculated from the receiver operating characteristic (ROC) curve. The ROC curve is a graph that shows the performance of a classification model at all thresholds. It consists of a sensitivity on the y-axis and a specificity of one on the x-axis for all possibilities. Sensitivity describes the accuracy of the model predicting presence, while specificity shows its effectiveness in predicting habitat suitability. To assess the model performance, MaxEnt used cross-validation to evaluate possible errors in the predictive output. The resulting AUC values ranged from 0.5 to 1.0, where values above 0.7 show appropriate model fit (Prasetyo et al. 2021). The accuracy of model performance based on AUC values is described in Table 3.

RESULTS

MaxEnt analysis of *A. gigas* distribution

Thirty-four distribution points of *A. gigas* were identified, spanning various districts in northern Sumatra, including southern Labuhanbatu Regency (eight points), northern Padang Lawas Regency (six points), southern Tapanuli Regency (six points), northern Tapanuli Regency (10 points), and Mandailing Natal Regency (Four points). The sample species was documented as featured in Image 1.

Habitat suitability analysis was conducted using MaxEnt with a distance resolution limit of 1 km^2 on the map. Among the 34 result points, MaxEnt covered 24 distribution points and the remaining 10 were used as sample points for testing. The remaining distribution points were then combined with the environmental variable map. Figure 4 shows MaxEnt results for *A. gigas* habitat in northern Sumatra with a range of 0–1, and 3b depicts the potential distribution in five suitability classifications. The red colour showed a highly suitable habitat with a probability range of 0.8–1, while the orange and yellow colours represented suitability

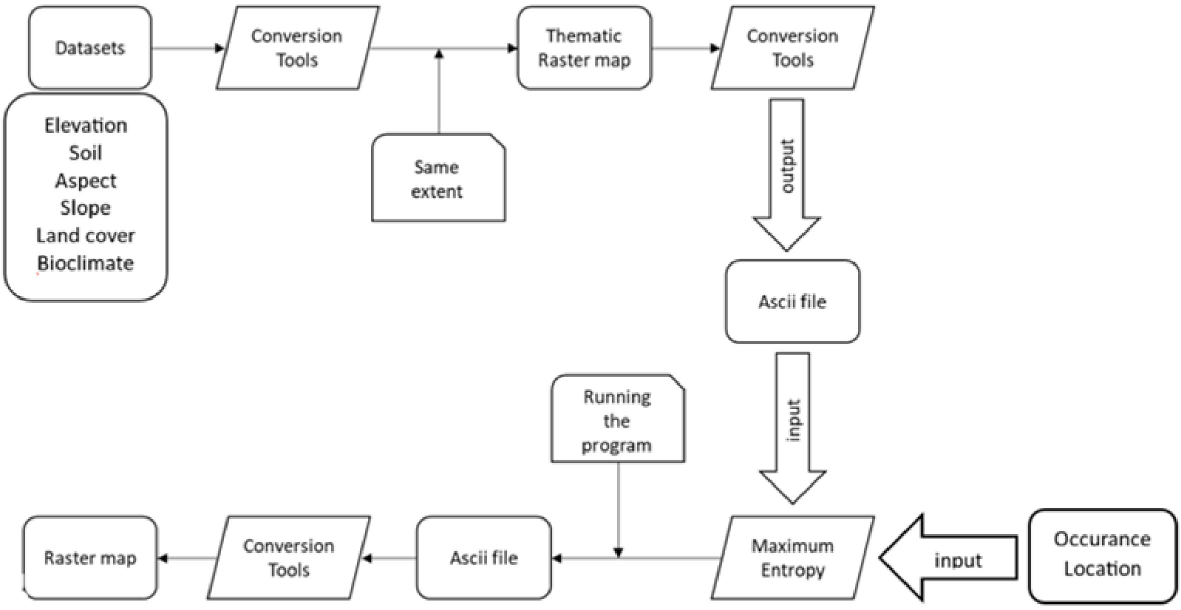

Figure 2. Type distribution mapping analysis procedure using MaxEnt and ArcMap tools.

Table 1. Data source or environmental variables for distribution modelling of *Amorphophallus gigas*.

	Data	Source	Type	Year
1	Digital Elevation Model (DEM)	www.earthexplorer.usgs.gov	.tif	2010
2	Soil Type	http://www.fao.org/soils-portal	.asc	2000
3	Aspect	Derived from DEM Data	.tif	2010
4	Slope	Derived from DEM Data	.tif	2010
5	Land cover	www.appgis.dephut.go.id	.kml	2000
6	Climate	www.worldclim.org	.bil	1980-2000

Table 2. Classification of habitat suitability of *Amorphophallus gigas* with probability of occurrence values

Main classification	Subclassification	Probability of occurrence
Suitable	Highly suitable	0.8–1
	Moderately suitable	0.6–0.8
	Marginally suitable	0.4–0.6
Not Suitable	Currently not suitable	0.2–0.4
	Permanently not suitable	0–0.2

class corresponding to a range of 0.6–0.8 and 0.4–0.6, respectively. The light blue colour showed areas not suitable for *A. gigas* with a probability range of 0.2–0.4 and the dark green colour implied areas very unsuitable with a probability range of 0–0.2.

Validation Model of *A. gigas* Habitats

The AUC test value was obtained from testing 30% of samples taken randomly. The higher the value, the better the accuracy of the data model. In this range, the AUC value fell into the good category from 0.8 to 1 by 0.971 for training data and 0.897 for test data. The model validation results are shown in Figure 5.

MaxEnt-derived models of *A. gigas* based on environmental variables

Environmental variables that contributed to MaxEnt analysis included elevation, slope, aspect, soil type, land cover, distance from roads, distance from rivers, average annual temperature (bio1), average monthly range (bio2), rainfall annual (bio12), and warmest quarterly rainfall (bio18). The modelling analysis results of habitat suitability showed that soil type, altitude, and average monthly temperature range had the highest contribution. The percentage contribution is shown in Table 4.

Jackknife analysis was used to calculate the importance of each environmental variable in the model and the results are shown in Figure 6. The green colour showed MaxEnt results without the variable included in the model, the blue colour showed the results obtained using only the variable, and the red colour implied the optimal results with all environmental variables. Soil type 20 (alluvial humic) has the highest impact on the

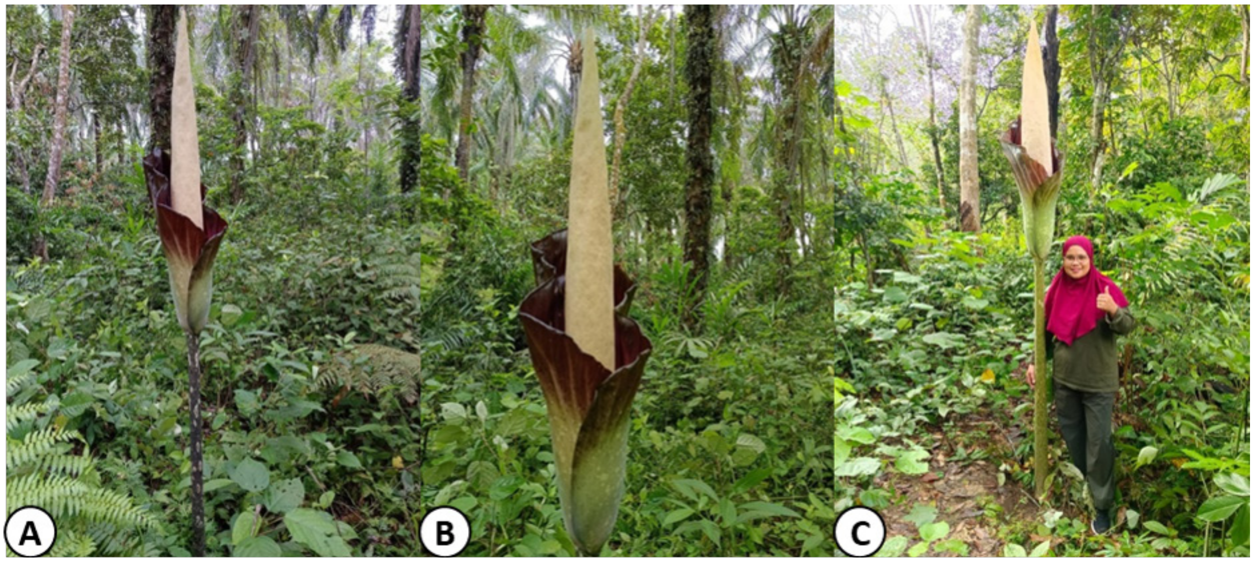

Image 1. An image series of *Amorphophallus gigas* includes: a—a close-up view | b—blossoming phase | and c—a depiction of the proportional height of *A. gigas* in comparison to a human. © Ridahati Rambey.

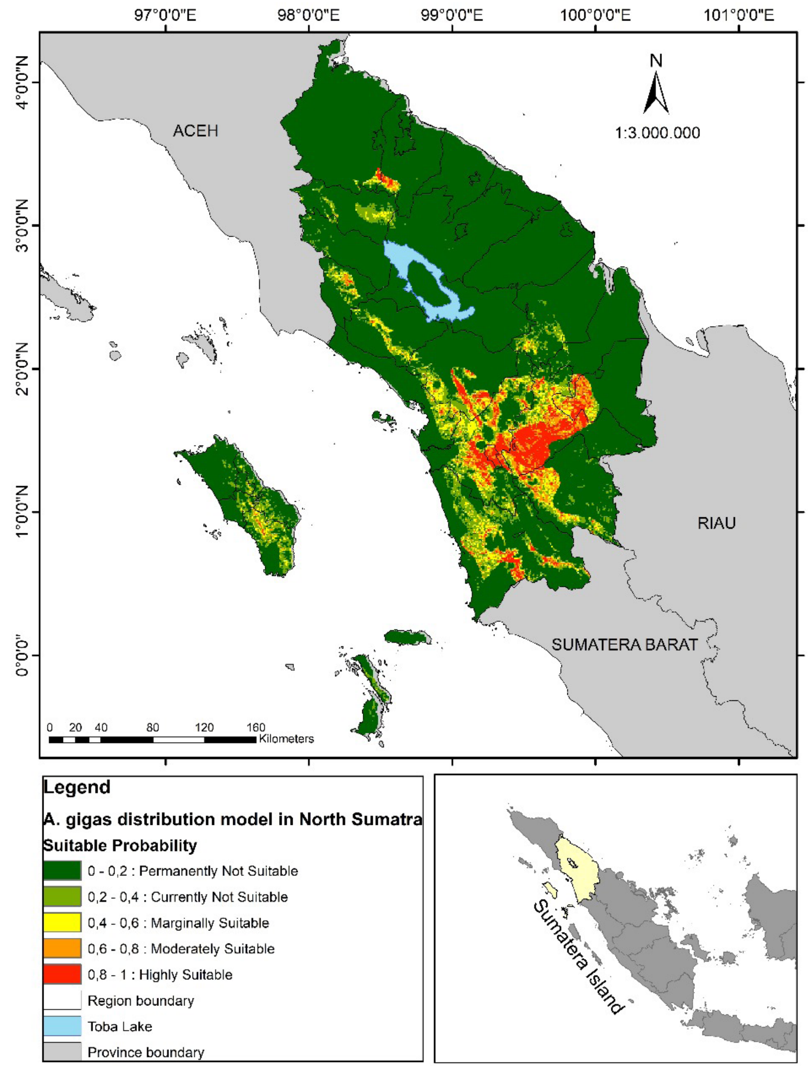

Figure 3. MaxEnt output map illustrating the *Amorphophallus gigas* habitat in northern Sumatra.

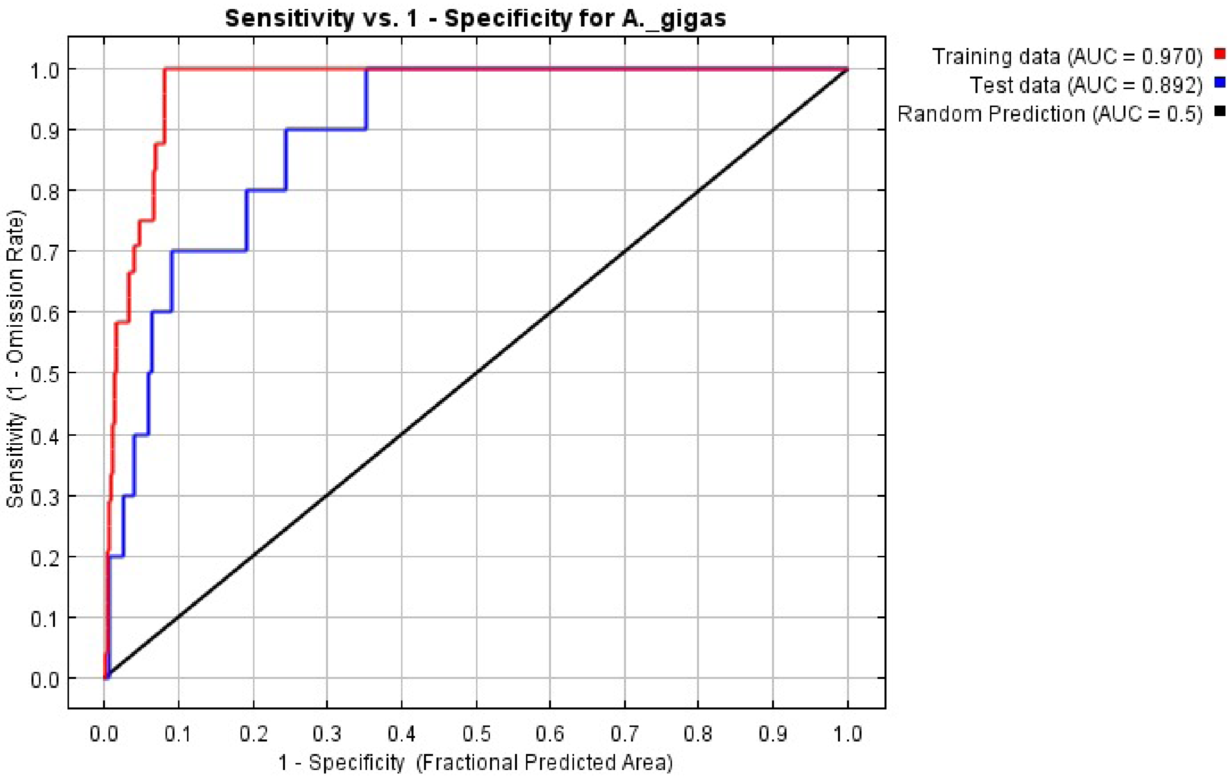

Figure 4. ROC graph showing sensitivity and specificity for *Amorphophallus gigas* distribution model. A higher AUC value shows the reliability of the model.

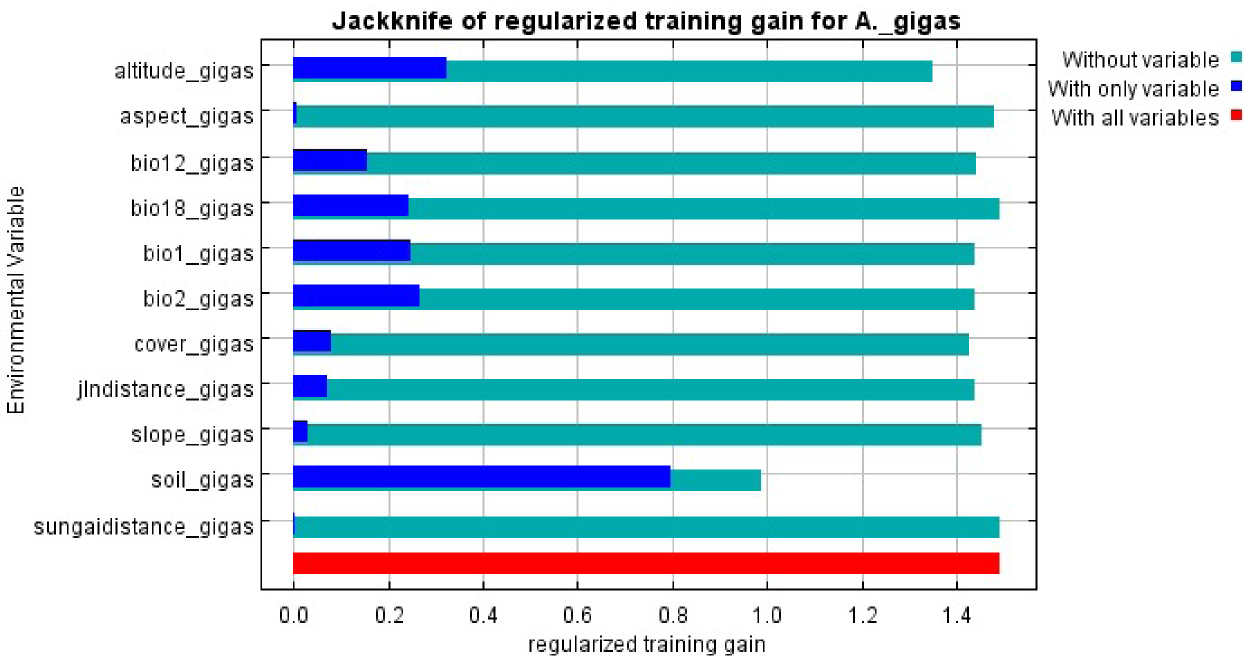

Figure 5. Jackknife analysis of *Amorphophallus gigas* for the importance of each environmental variable in the model.

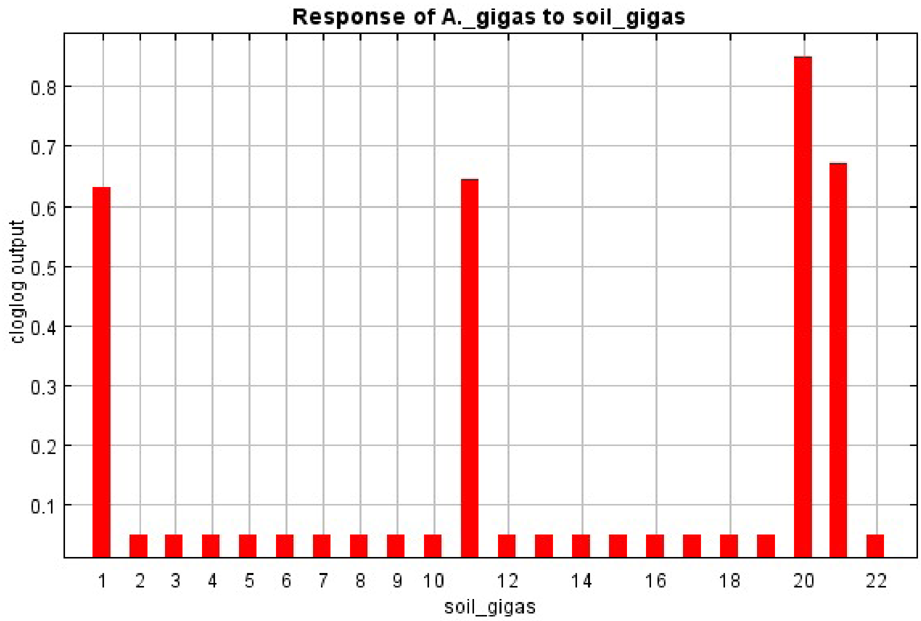

Figure 6. Response of *Amorphophallus gigas* to soil type variables.

Table 3. Model performance accuracy based on AUC values.

AUC Value	Model Performance
0.6 – ≤ 0.7	Not accurate
> 0.7 – ≤ 0.8	Moderately
> 0.8–0.9	Accurate

distribution of *A. gigas*. The response of *A. gigas* to soil-type variables is shown in Figure 7. The response of *A. gigas* the most significant contribution stemming from soil type 1: Ah27-2/3c (Humic Acrisols), 11: Th17-2c (Humic Andosol), 20: Jd 9-2/3a (District Fluvisols), and 21: Bh 17-2bc (Humic cambisols).

The response of *A. gigas* to the environmental variables of altitude and the difference between the annual average maximum and minimum temperatures are shown in Figure 8. Height from 400 to 600 m was classified as the highest probability distribution with a value above 0.5. Regarding the difference in annual average maximum and minimum temperatures, the range of 10–10.5^{0}C had the highest probability. In other words, *A gigas* would be found less frequently when the difference between the maximum and minimum temperatures in the annual average exceeds 10.5 or falls below 10^{0}C.

Distribution of *A. gigas* in the northern Sumatra Region

MaxEnt results in Figure 9 showed that 15 regions in northern Sumatra were suitable for the distribution of *A. gigas* with varying areas, ranging from 175.19 ha to 43,248.57 ha. This was less than 30% of the total land area in the province, and the most suitable area was located in the southern part. The results of the map modelling showed that the most suitable areas for the growth of *A. gigas* were in the northern Padang Lawas (113,916.34 ha), southern Tapanuli (43,248.57 ha), southerns Labuhanbatu (17,759.81 ha), Mandailing Natal (17,735, 23 ha), and northern Tapanuli Regency (16,305.74 ha). For the distribution of *A. gigas* based on land cover types, the majority is located in cropland or dry land agriculture, accounting for 52.78% of its presence. Meanwhile, agroforestry areas constitute 33% of its habitat, and forested areas make up 13.2%. It appears that *A. gigas* favors environments where the canopy cover is relatively sparse, as evidenced by its prevalence in agroforestry and crop areas, which typically feature less dense vegetation.

DISCUSSION

The map modeling results indicate that the most suitable habitats for *A. gigas* growth are concentrated in specific regions with favorable geographical conditions. These areas likely possess suitable environmental factors, such as soil type, elevation, and climate, supporting the species' growth and distribution. Furthermore, based on the analysis results, the variables that influenced the habitat suitability of *A. gigas* included soil type, monthly

Table 4. Percentage contribution of the three highest environmental variables in MaxEnt *Amorphophallus gigas* model.

	Variable	Variable code	Percent contribution (%)
1	Type of soil	soil_gigas	55
2	Average monthly temperature range	bio2_gigas	16.2
3	Elevation	altitude_gigas	7.9
4	Distance from road	jlndistance_gigas	5.3
5	Average annual temperature	bio1_gigas	4.4
6	Land use and land cover	cover_gigas	4.3
7	Warmest quarterly rainfall	bio18_gigas	3.4
8	Slope	slope_gigas	1.8
9	Aspect	Aspect_gigas	0.8
10	Annual rainfall	bio12_gigas	0.8
11	Distance from the river	Sungaidistance_gigas	0

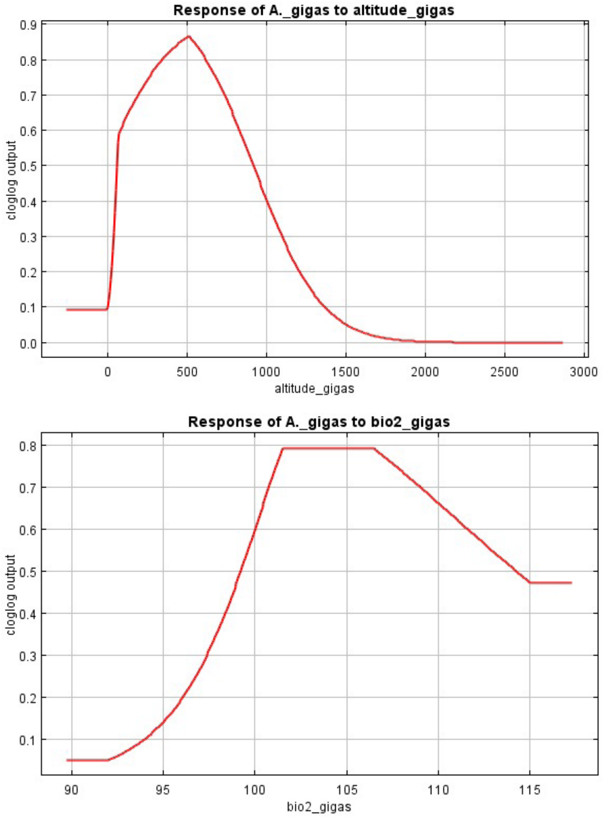

Figure 7. Response of *Amorphophallus gigas* to altitude and to the difference in annual average maximum and minimum temperature.

temperature, and altitude (Figure 4). A machine learning ensemble model employing Random Forest and Artificial Neural Network methods identified slope and distance to the nearest river as the two most significant variables correlated with the growth of *A. titanum* in Sumatra (Yudaputra et al. 2022). The most suitable area for the growth of *A. gigas* was at an altitude of 400–600 m (Figure 6).

The land suitability analysis indicated the highest potential growth point for *Amorphophallus* at 438 m and the lowest at 24 m in the Kokok Tojang sub-watershed in eastern Lombok (Wahyu et al. 2022). Another study explored the habitat characteristics of *A. titanum* populations in Lampung across seven locations, including three in the TNBBS, two in protected forests, and two in community forests (Munawaroh et al. 2017). Additionally, a study on the distribution of *porang* (*Amorphophallus muelleri*) based on regional topography in Malang Raya, utilizing Quantum GIS software, revealed that the species was found at varying heights ranging from 34 to 931 m and 100 to 1,100 m (Alifianto et al. 2013). The findings indicated that *A. gigas* generally flourished in agroforestry stands, aligning with previous studies that reported the plant's wild growth in various regions across northern Sumatra (Rambey et al. 2021). Furthermore, *A. gigas* was observed under rubber stands in northern Padang Lawas Regency, Indonesia. The plant was identified in Sabungan Village and Langgapayung Village, southern Labuhanbatu Regency, thriving under *Hevea brasiliensis* stands (Yudaputra et al. 2022; Rambey et al. 2022b).

The validation results of all selected variables showed that the AUC value for *A. gigas* habitat suitability model was 0.970. This shows the model created can be used and has high accuracy (Pradhan & Setyawan 2021). The AUC method, employed in the validation process, is a standard technique for assessing the validity of a model. It also offers advantages for users by helping to avoid subjectivity in the boundary selection process (Lobo et al. 2008). MaxEnt modelling showed three main variables determining the distribution of *A. gigas* in northern Sumatra, with the soil variable having the most significant contribution. Based on the results, Fluvisol, Andosol, Acrisol, and Cambisols soils were found to be suitable as habitats. Humic Acrisols are characterized by acid soils with layers of clay accumulation. According to the modified legend, this class consists only of clays with low cation exchange capacity. Andosol represents dark soil formed from volcanic material with little horizon development. Fluvisols comprise alluvial and floodplain soils with little profile development, while Cambisol is soil with little profile development and not dark in colour (Soil Survey Staff 2010, 2014). As a member of the Araceae family, the *Amorphophallus* species can grow in almost all types of soil, but optimal growth and

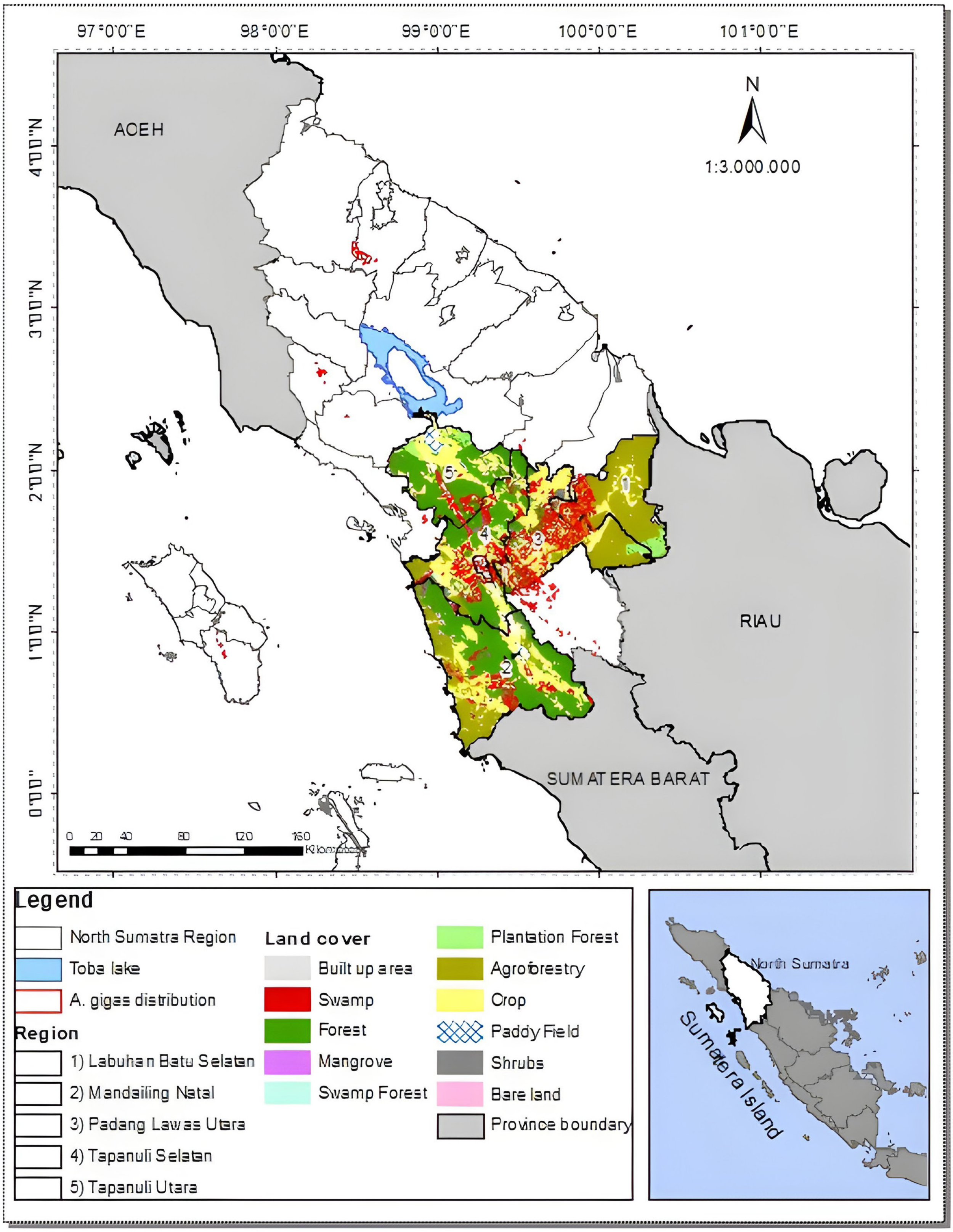

Figure 8. Potential distribution and extent of *Amorphophallus gigas* in northern Sumatra in various land covers.

development are achieved in loose soil, with a neutral pH and good drainage (Santosa et al. 2008). In general, *Amorphophallus* grows optimally in soil having a pH of 6.07.5 with a light texture (sandy clay or loose), rich in nutrients, and high in humus content (Shenglin et al. 2020). This is in line with the modelling results showing neutral pH and high humus in the preferred soils. In the section analyzed, there were many types of alluvial, andosol, and podzolic soils with relatively high levels of soil fertility.

In MaxEnt analysis, temperature played a crucial role as a tuning parameter, impacting the complexity of the model. The addition of environmental variables can also affect the value of the "regularization multiplier" parameter and the number of background points used in modelling. The addition of environmental variables such as temperature increased the ability of the MaxEnt model to predict the possibility of species existence (Elith et al. 2011). The Jackknife AUC test used the height on the graph as an important indicator of environmental variables influencing species modelling. Altitudes signify the importance of a variable in influencing species existence, while slope indicates the sensitivity of the model to that specific variable (Bradie & Leung 2017). *Amorphophallus* species thrives in lowland areas up to 1,000 m with a monthly rainfall range of 300–500 mm during the growth period. The optimal air temperature for *A. gigas* falls within the range of 20–30 °C. Exceeding 35 °C may result in leaf burning, while low temperatures might induce dormancy. To ensure high production, it is recommended to provide 50–60% shade (Nugrahaeni et al. 2021).

Amorphophallus species are known to grow and disperse from lowland areas up to 1,000 m, with optimal temperatures ranging between 25–35°C and monthly rainfall between 300–500 mm during the growth period (Puspitaningtyas & Ariati 2016). This finding is consistent with our MaxEnt analysis, which shows the species' presence at altitudes of approximately 500 m, within a broader range of 100–1,000 m. The temperature variation between annual maximum and minimum averages is approximately 10°C (Figure 6). Similarly, Wulandari et al. (2022) highlight the impact of temperature on the distribution of *A. gigas*, noting that it is predominantly found at elevations of 200 to 500 m. These studies underscore the importance of understanding the bioecology and distribution patterns of *Amorphophallus* species, which is essential for supporting effective conservation efforts (Nursanti et al. 2019; Mutaqin et al. 2022).

In addressing the conservation needs of *A. gigas* in northern Sumatra, several strategic measures are recommended. Firstly, the establishment of protected areas is crucial to protect the habitat from degradation. These protected regions could be strategically designated within existing agroforestry lands, encompassing conservation zones or buffer zones around critical habitats to mitigate impacts from adjacent land uses. Implementing regulations to manage land use effectively can prevent habitat destruction and promote the persistence of *A. gigas* populations. Moreover, the adoption of sustainable forestry practices is essential to balance ecological health with economic activities. This strategy includes maintaining ecological functions while allowing for controlled agroforestry operations that do not compromise the habitat integrity of *A. gigas*. Ongoing ecological monitoring and regular surveys should be conducted to track the population dynamics, distribution, and occurrence of *A. gigas*. This data is invaluable for evaluating the effectiveness of conservation interventions and adapting strategies as necessary. Finally, fostering collaborations with international organizations, research institutions, and conservation groups can enhance the conservation output for *A. gigas*. By sharing knowledge, resources, and best practices, these partnerships can amplify efforts and innovate conservation approaches tailored to the unique ecological context of northern Sumatra. This integrated approach will not only contribute to the conservation of *A. gigas* but also support the broader biodiversity and ecological health of the region.

CONCLUSION

The distribution suitability of *A. gigas* varied, ranging 175.19–113,916.34 ha, with less than 30% of the land area in northern Sumatra being suitable. The most suitable area was identified in the southern part of the province. In conclusion, almost all districts in northern Sumatra were found to be suitable for the growth of *A. gigas*, with the largest areas situated in the altitude range of 400–600 m. The data generated from this study could serve as a basic reference in conservation and propagation efforts to harness the numerous benefits.

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Abstrak: *Amorphophallus gigas* hanya ditemukan di kebun agroforestri masyarakat di wilayah Sumatra bagian utara, Indonesia. Spesies ini menghadapi berbagai ancaman terhadap populasinya, termasuk konversi lahan dan pengambilan umbi untuk tujuan ekonomi. Meskipun memiliki karakteristik habitat yang unik, status konservasinya belum tercatat dalam IUCN *Red List*. Konservasi yang efektif memerlukan data komprehensif, termasuk distribusi dan kondisi habitat di lapangan. Oleh karena itu, penelitian ini bertujuan untuk menganalisis variabel-variabel yang memengaruhi distribusi *A. gigas* di Sumatra bagian utara serta memprediksi luas area potensial penyebarannya. Variabel yang dikaji meliputi ketinggian, kemiringan, arah lereng, kondisi iklim, dan tutupan lahan. Titik koordinat diambil langsung di lapangan menggunakan GPS, sedangkan pemodelan MaxEnt (*Maximum Entropy*) digunakan untuk memprediksi kesesuaian habitat spesies ini. Pemodelan MaxEnt menunjukkan bahwa tipe tanah memiliki kontribusi terbesar terhadap distribusi *A. gigas* (55%), diikuti oleh kisaran suhu rata-rata bulanan (16%), dan ketinggian (7,9%). Area dengan kesesuaian habitat tertinggi ditemukan di bagian selatan provinsi. Hasil penelitian ini bermanfaat sebagai rumusan dalam perancangan strategi konservasi bagi *A. gigas*.

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Author contributions: RR—conceptualized the study, conducted fieldwork, developed the methodology, curated the data, performed formal analysis, investigated the study, and drafted the original manuscript. R—supervised the project, secured funding, investigated the study, managed project administration, and contributed to drafting the manuscript. AR—supervised the project, provided resources, and performed formal analysis. ESMN—supervised the project, conducted formal analysis, and visualized the outputs. D, TAA—validated the research outputs. MHI—contributed to methodology development, while MHS—developed the methodology, conducted formal and software analyses, visualized the outputs, and editing. SG, MNS—contributed to manuscript writing and editing.

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