

# Mapping Potential Midas Cichlid Spread for Invasive Population Control in Indonesian Waters

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**Abstract.** *A. citrinellus* (Midas Cichlid) is an invasive fish species introduced to Indonesian waters through the ornamental fish trade. This species poses a serious threat to native fish populations through predation, competition, and habitat alteration. This study aims to determine priorities in the management and elimination of the Midas Cichlid in high-risk areas in Indonesian freshwater environments using species distribution modelling. The Maximum Entropy (MaxEnt) algorithm was used with 20 validated presence records and six bioclimatic variables (BIO 2, 4, 8, 15, 18, and 19), which were selected through Pearson correlation analysis and Variance Inflation Factor. Model performance was evaluated using the AUC (Area Under Curve) metric and jackknife analysis. The model showed remarkable predictive efficacy, with an average AUC value of 0.955 (SD = 0.017). Seasonal rainfall contributed 28%, followed by seasonal temperature 26.9% and cold quarter rainfall 24.2%. The optimum suitability zone is largely located in Java, Bali, Lombok, South Kalimantan, Central and Southeast Sulawesi, and several areas of Papua. These included important habitats for endemic and endangered species such as *Betta burdigala*, *Chilatherina sentaniensis*, and *Oxyeleotris heterodon*. The integrated implementation of population suppression techniques, including trade restrictions, habitat rehabilitation, and continuous monitoring are critical for reducing invasive populations.

## 1 Introduction

The global ornamental fish trade has become an important economic industry, with enthusiasts around the world drawn to the extreme beauty of colours and patterns in diverse combinations [1]. *A. citrinellus* belongs to the Cichlidae family, which entered through the largest introduction route, namely the ornamental fish trade [2]. *A. citrinellus* is known as the

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Midas cichlid, originating from Nicaragua and Costa Rica in Central America. The Midas cichlid has colours ranging from blackish gray to golden yellow [3]. This species has thick lips, strong teeth, and a hard ygeal jaw apparatus that allows the Midas to adapt quickly to various types of food [4]. The species *A. citrinellus* belongs to the Cichlidae family, which is considered the most invasive in Indonesian inland waters. In addition to their shiny appearance, they are attractive because of their adaptability, minimal care requirements, and aggressive behaviour. Their bright colours and active movements symbolize energy and good luck, which are the main reasons for their involvement in the Asian ornamental fish trade.

This popularity has led to the illegal disposal of aquariums by irresponsible individuals when they realize that cichlids require demanding maintenance. The Midas Cichlid's habitat is primarily tropical waters with temperatures of 21-26°C and a pH between 6-8. *Amphilophus sp.* is believed to have entered Indonesian public waters through accidental introduction due to the escape of fry carried away by currents during stocking in floating net cages [5]. Its history of appearance is also linked to stocking activities in the Jatiluhur and Sermo reservoirs in 1995, the Kedung Ombo reservoir in 2000, and the Sentani reservoir in 2005 [6], accompanied by the release of a number of individuals into the wild by ornamental fish hobbyists. The introduction of *A. citrinellus* poses a threat to the structure of local aquatic habitats due to their natural predatory nature and rapid growth.

The invasion of the species shows a dramatic pattern of temporal expansion since they first entered Indonesian waters in the mid-1990s. At Jatiluhur Reservoir, red devil fish catches increased from 40% in 2003-2004 to still reaching 30% in 2011, with production reaching 4,131.5 kg/year in the 2011-2012 period. More extreme population dynamics were documented in Lake Sentani, Papua, where red devil cichlids accounted for 87.2% of total fish catches in a 2018 survey with a very low Shannon-Wiener diversity index ( $H'=0.57$ ), indicating extraordinary ecological dominance. This temporal expansion is also reflected in Lake Batur, Bali, where the midas cichlid has come to dominate up to 60% of the entire fish population, threatening the survival of previously stable endemic species. The decline in native species populations is evident in Lake Sentani with the drastic reduction of the endemic Sentani snakehead (*Oxyeleotris heterodon*), which has high economic value (Rp 100,000 per fish), while at Sermo Reservoir, fishermen's daily catch decreased from 5 kg in 2005 to only 4 kg in the following period, with approximately 75% consisting of red devils. Population dynamics research at Sermo Reservoir in 2021-2022 showed that *Amphilophus spp.* had a growth rate with the equation  $L_t = 19.3 [1 - e^{0.31(t+0.61)}]$ , indicating rapid growth and high recruitment capacity as drivers of continued dominance. This invasion pattern is consistent with studies in various Indonesian waters, where the presence of this invasive species systematically shifts local fish communities towards ecosystems dominated by invasive cichlids with low diversity.

Given the rapid invasive expansion and widespread distribution patterns, Species Distribution Modelling (SDM) using the Maximum Entropy (MaxEnt) algorithm has become a powerful predictive tool for estimating the potential distribution of these two invasive cichlid species to new waters. The SDM model integrates species distribution data with environmental variables such as temperature, precipitation, elevation, water quality, and anthropogenic factors (human density, transportation frequency, aquaculture activities) to identify habitats suitable for the spread of invasive species. Using the MaxEnt algorithm optimized through the ENMeval package with the best feature combinations (FC) and regularization multiplier (RM) parameters, the model achieved an AUC (Area Under Curve) value of 0.88-0.90, indicating high prediction accuracy for forecasting the spatial expansion of *A. citrinellus*. The study shows that the integration of environmental variables from the native range and the invaded range, as well as anthropogenic factors, results in superior model performance compared to the use of climate variables alone. This SDM approach enables the identification of high-vulnerability zones (hotspots) for invasion in uncolonized waters,

thereby informing more effective monitoring and invasive species management intervention priorities. Furthermore, SDM projections under future climate change scenarios (RCP 4.5 and RCP 8.5) indicate that certain regions in Indonesia, particularly Java and other tropical areas, will experience increasing habitat suitability for colonization by both cichlid species, with potential expansion reaching 6-12% of the total area in the period 2050-2070. Thus, the application of SDM as a forecasting tool is crucial for anticipating the invasive spread patterns of *A. citrinellus* to new waters, while also identifying windows of opportunity for the implementation of proactive and targeted control strategies at the landscape level.

## 2 Research and Methods

### 2.1 Environmental Variables

Twelve initial bioclimatic variables (BIO 2, 3, 4, 6, 8, 10, 11, 12, 15, 17, 18, and 19) were selected as candidate environmental predictors with comprehensive descriptions presented in Table 1. All bioclimatic raster data were downloaded for the Indonesian mainland and integrated into a uniform coordinate system with consistent spatial resolution before being entered into the modelling analysis stage. Multicollinearity evaluation among the twelve bioclimatic variables was performed using RStudio software through two sequential procedures: first, Pearson correlation calculations to identify variable pairs showing strong correlations with absolute values  $|r| > 0.7$ , followed by the selection of one variable from each pair based on ecological relevance considerations; second, the calculation of the Variance Inflation Factor (VIF) using the R programming package to verify that all selected variables had a VIF value  $< 10$ . This rigorous variable selection procedure resulted in a set of bioclimatic variables that were independent of each other and did not contain redundant information, which were then used as predictors in modelling the spatial distribution of the two invasive cichlid species.

**Table 1.** Description and operational definition of environmental variables (Bioclim) as initial inputs in modelling

Code	Variables names	Definition
BIO2	Mean Diurnal Range	Average of (monthly maximum temperature – monthly minimum temperature)
BIO3	Isothermality	BIO2 divided by BIO7, multiplied by 100. (Measures diurnal variation relative to annual range)
BIO4	Temperature Seasonality	Standard deviation of monthly average temperature multiplied by 100. (Measures the magnitude of temperature fluctuations throughout the year)
BIO6	Min Temperature of Coldest Month	The minimum temperature of the coldest month of the year.
BIO8	Mean Temperature of Wettest Quarter	Average temperature during the quarter (three consecutive months) with the highest rainfall.
BIO10	Mean Temperature of Warmest Quarter	Average temperature during the warmest quarter (three consecutive months).
BIO11	Mean Temperature of Coldest Quarter	Average temperature during the coldest quarter (three consecutive months).

BIO12	Annual Precipitation	Total annual rainfall
BIO15	Precipitation Seasonality	The coefficient of variation (CV) of monthly rainfall (standard deviation divided by monthly average, multiplied by 100) – measures how “seasonal” rainfall is.
BIO17	Precipitation of Driest Quarter	The amount of rainfall during the quarter (3 consecutive months) with the lowest rainfall.
BIO18	Precipitation of Warmest Quarter	The amount of rainfall during the quarter (3 consecutive months) which is the warmest quarter (based on temperature).
BIO19	Precipitation of Coldest Quarter	The amount of rainfall during the quarter (3 consecutive months) which is the coldest quarter (based on temperature).

## 2.2 Distribution Modelling Evaluation

Potential distribution modelling for Midas Cichlid utilized the maximum entropy (MaxEnt) algorithm, incorporating species presence points and selected bioclimatic predictors. Model precalibration occurred in the RStudio environment via the ENMeval package, employing a spatial block-based cross-validation scheme to minimize spatial leakage bias. The evaluated parameter space encompassed four feature class (FC) types—Linear (L), Linear+Quadratic (LQ), Hinge (H), and Linear+Quadratic+Hinge (LQH)—combined with regularization multiplier (RM) values of 0.5, 1.0, 2.0, and 3.0. Selection of the optimal parameter combination relied on three complementary criteria: the  $\Delta AICc$  (delta Akaike Information Criterion corrected) value, prioritizing minimal values ( $\leq 2$ ) for model parsimony; validation AUC (Area Under the Receiver Operating Characteristic Curve) to assess discriminatory power on independent data; and the AUC difference (training AUC – validation AUC) to indicate overfitting levels [7].

The optimal parameter combination subsequently served to train the final MaxEnt model using the complete set of species presence points. Performance evaluation focused on the prediction-omission curve for threshold calibration and the sensitivity-specificity curve (ROC) for discriminatory capability. Classification of model performance followed literature standards based on AUC values, defining 0.9–1.0 as “excellent”, 0.8–0.9 as “good”, 0.7–0.8 as “fair”, 0.6–0.7 as “poor,” and approximately 0.5 as “no discriminatory power” [7]. Visual interpretation of the model output relies on a habitat suitability index ranging from 0 to 1, depicted through a continuous color gradient starting with green (0), transitioning to yellow (0.5), and culminating in red (1). Final evaluation metrics appear as mean values and standard deviations to capture model variability.

## 2.3 Species Occurrences

The spatial distribution analysis of the Midas Cichlid (*Amphilophus citrinellus*) covers the entire territory of Indonesia at coordinates 11°S - 6°N and 95°E - 141°E. This archipelagic country has a high diversity of freshwater systems, ranging from tropical lowlands to mountain reservoirs, with monsoon climate characteristics and warm water temperatures throughout the year. This environmental heterogeneity provides ideal conditions for studying the potential for invasive species expansion on a national scale. The presence of *A. citrinellus* in Indonesian waters has been recorded since the 1990s through the ornamental fish trade and shows a dynamic pattern of spread, making the identification of areas at high risk of colonization a crucial step.

**Table 2.** Species occurrence record of *Amphilophus citrinellus* in Indonesia.

Species	Location	Georef.	Reference
<i>A. citrinellus</i>	Lake Batur, Bali	-8.223809, 115.418253	[8]
<i>A. citrinellus</i>	Lake Batur, Bali	-8.255481, 115.400021	[8]
<i>A. citrinellus</i>	Lake Batur, Bali	-8.263667, 115.419557	[8]
<i>A. citrinellus</i>	Lake Batur, Bali	-8.272424, 115.411330	[8]
<i>A. citrinellus</i>	Lake Batur, Bali	-8.281377, 115.388176	[8]
<i>A. citrinellus</i>	Sermo Reservoir, Sidowayah, Yogyakarta	-7.817916, 110.114535	[9]
<i>A. citrinellus</i>	Sermo Reservoir, Tegalrejo, Yogyakarta	-7.818068, 110.118790	[9]
<i>A. citrinellus</i>	Sermo Reservoir, Tegiri, Yogyakarta	-7.822985, 110.110736	[9]
<i>A. citrinellus</i>	Sermo Reservoir, DAM Klepu, Yogyakarta	-7.825613, 110.118900	[9]
<i>A. citrinellus</i>	Lake Beratan, Bedugul, Bali	-8.4096, 115.1889	[10]
<i>A. citrinellus</i>	Jembatan 12 River, Bangka Belitung	-2.131141, 106.094306	[8, 11]
<i>A. citrinellus</i>	Kedung Ombo Reservoir	-7.254260, 110.833506	[12]
<i>A. citrinellus</i>	Lahor Reservoir, Malang	-8.144619, 112.452117	[12]
<i>A. citrinellus</i>	Jatiluhur Reservoir	-6.52361, 107.38833	[7]
<i>A. citrinellus</i>	Cirata Reservoir, DAS Citarum	-6.750827, 107.278425	[14]
<i>A. citrinellus</i>	Lake Sentani, Yakonde, Papua	-2.578412, 140.400577	[6]
<i>A. citrinellus</i>	Lake Sentani, Ayapo, Papua	-2.631114, 140.595364	[6]
<i>A. citrinellus</i>	Lake Sentani, Ifale, Papua	-2.608211, 140.524884	[6]
<i>A. citrinellus</i>	Lake Sentani, Asei, Papua	-2.602560, 140.575557	[6]

Data collection on the presence of *A. citrinellus* was conducted through a comprehensive literature review. A rigorous data validation process was implemented to ensure model robustness. This included: (1) Duplicate removal: eliminating identical records from the same source; (2) Coordinate verification: cross-referencing points with satellite imagery to ensure they were situated in freshwater bodies; and (3) Temporal alignment: ensuring records

coincided with the period of environmental data. The final curated dataset consisted of 19 unique, spatially independent occurrence points used for Maxent modelling.

## **2.4 Map Visualisation**

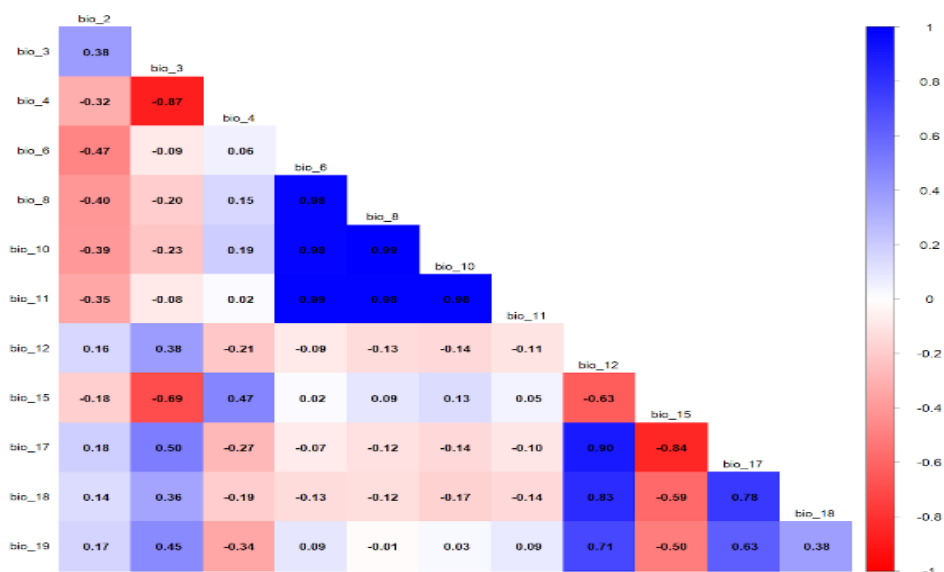
Spatial visualisation of the predicted distribution of the Midas Cichlid was processed using ArcMap software. The MaxEnt model output in raster format was integrated into a geographic information system for presentation of the final map. Habitat suitability was represented using continuous colour gradation symbolisation ("stretched") based on a probability value range of 0 to 1. Areas with values close to 0 were displayed using green colours, indicating low habitat suitability or minimal invasion risk. The transition of the colour spectrum towards yellow signified moderate suitability. Red is used specifically to visualise areas with values close to 1, which represent highly suitable habitats or areas with a high risk of colonisation. Standard cartographic elements, including a north arrow, bar scale, and geographic coordinate grid, are added to the map layout to ensure accuracy and ease of spatial interpretation.

## **3 Results**

### **3.1 Screening of the Main Environmental Variables**

Pearson correlation analysis conducted on 12 initial bioclimatic variables identified four pairs of variables that showed very high correlation coefficients, exceeding the threshold  $|r| > 0.7$ : BIO 3 and BIO 4 ( $r = -0.87$ ), BIO 6 and BIO 8 ( $r = 0.98$ ), BIO 10 and BIO 11 ( $r = 0.98$ ), and BIO 15 and BIO 17 ( $r = 0.90$ ). Additional variable pairs show strong correlations indicating information redundancy, including BIO 17 and BIO 18 ( $r = 0.78$ ), BIO 15 and BIO 18 ( $r = -0.59$ ), BIO 3 and BIO 15 ( $r = -0.69$ ), and BIO 4 and BIO 19 ( $r = -0.34$ ). Variance Inflation Factor (VIF) diagnostics show that all retained variables have VIF values well below the 10 threshold, with a maximum value of 1.977 for BIO 15 and a minimum value of 1.235 for BIO 8. This pattern of multicollinearity provides an empirical basis for variable selection, allowing the elimination of redundant information while maintaining optimal ecological representation for species distribution modelling.

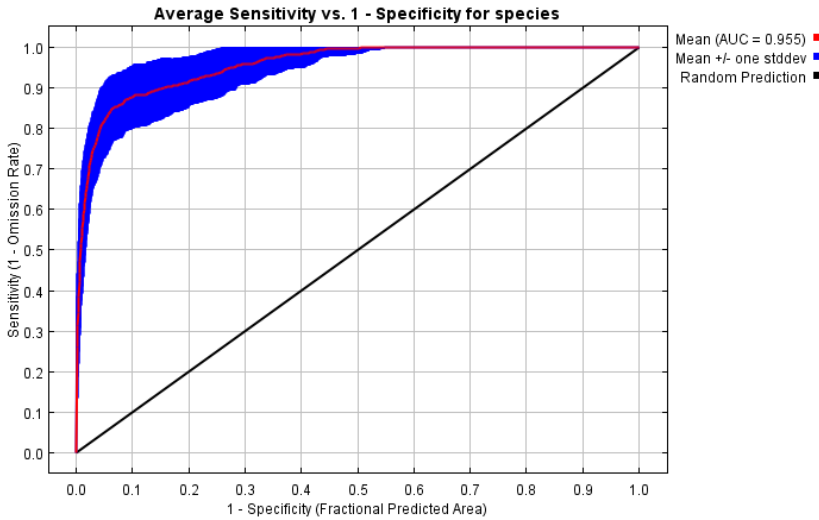
This selection procedure yielded six final variables, BIO 2, BIO 4, BIO 8, BIO 15, BIO 18, and BIO 19. All satisfy the statistical multicollinearity criteria while providing ecologically representative variables for spatial distribution analysis of both invasive fish species in Indonesia.



**Fig 1.** Pearson correlation test result of Bioclim representation for *Amphiophus citrinellus*.

### 3.2 Modelling Performance

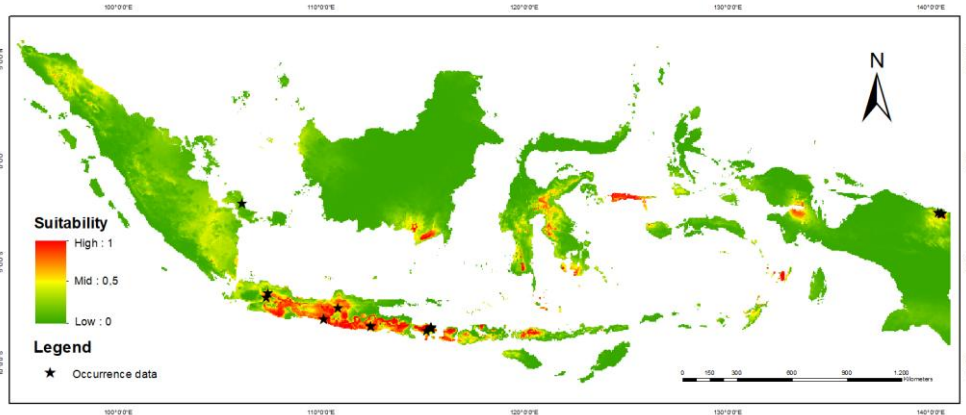
The MaxEnt model developed to predict the spatial distribution of Midas Cichlids in Indonesia demonstrated excellent predictive performance with a mean Area Under the Curve (AUC) value of 0.955 (SD = 0.017), indicating exceptionally high discrimination capacity between locations with invasive fish presence and those without. Receiver Operating Characteristic (ROC) curves demonstrated substantial consistency across model replications, with consistently high sensitivity across variable specificity thresholds, enabling the model to identify approximately 90% of potential invasive fish presence areas whilst minimising false positive rates. The low standard deviation (0.017) indicates robust stability and reliability of the MaxEnt model predictions across all replications. This superior performance reflects the high effectiveness of the selected environmental variables in capturing habitat preferences of Midas Cichlids. Given this level of performance, the model meets the "excellent" standard for ecological modelling and is suitable for implementation in invasive species management decision-making. The model's high capability in detecting potential invasive presence areas (high sensitivity) is particularly critical for proactive prevention prior to population expansion into new geographic regions, whereas high specificity based on predicted area optimises management resource allocation by reducing false area identifications that lack genuine invasive presence risk. These findings confirm that MaxEnt represents a robust and reliable methodology for spatial prediction of invasive fish distribution within Indonesian aquatic ecosystems and can serve as the foundation for spatially-informed management and monitoring strategies.



**Fig 2.** Receiver Operating Characteristic (ROC) curves of MaxEnt model replications.

### 3.3 Modeled Current Potential Distribution

The spatial distribution map derived from MaxEnt analysis illustrates the potential habitat suitability for Midas Cichlid (*A. citrinellus*) throughout Indonesia, with suitability classifications ranging from low at 0 (represented in green) to high at 1 (represented in red). Zones of highest suitability (red-orange) are concentrated along freshwater aquatic systems in Java, particularly in the southern region encompassing major river systems and interconnected water bodies, alongside circumscribed zones in North and Southeast Sulawesi. This distribution pattern reflects species habitat preferences regarding specific environmental conditions including moderate to high water temperature, particular water quality characteristics, and suitable habitat types. Zones of moderate to high suitability (orange–yellow) exhibit more extensive geographic coverage, encompassing eastern Java, southern Sumatra, Kalimantan, and aquatic systems in Maluku, representing areas with invasive establishment potential yet characterised by less optimal environmental conditions compared to priority zones. Conversely, green zones with low suitability dominate northern Sumatra, North Kalimantan, and Papua, indicating environmental conditions (lower temperature regimes, distinct hydrological characteristics) insufficiently conducive to stable invasive population establishment. This spatial pattern aligns with documented occurrences of *A. citrinellus* in Indonesian freshwater systems distributed across Java, Sumatra, and Sulawesi. This cartographic output holds critical significance for invasive species management as it delineates high-priority zones (red-orange) requiring intensive monitoring and proactive control interventions to prevent further dispersal, whilst moderate suitability zones warrant inclusion in periodic monitoring programmes, and low suitability zones may serve as focal areas for preventative surveys to detect nascent populations prior to expansion into zones of higher suitability.



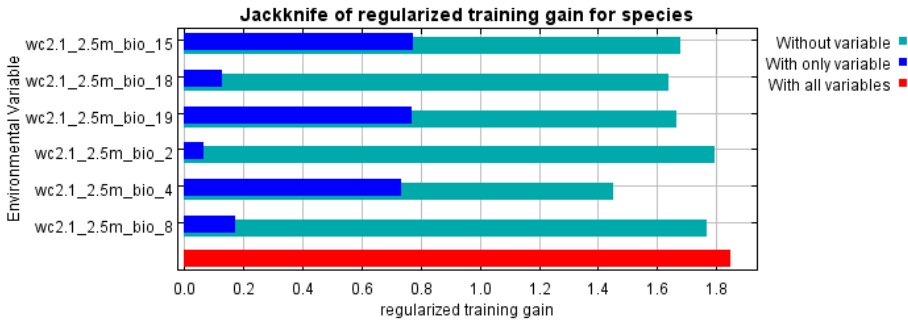
**Fig 3.** Potential distribution and occurrence map of *A. citrinellus* based on suitability of bioclimate condition in Indonesia.

### 3.4 Contribution of environmental variables

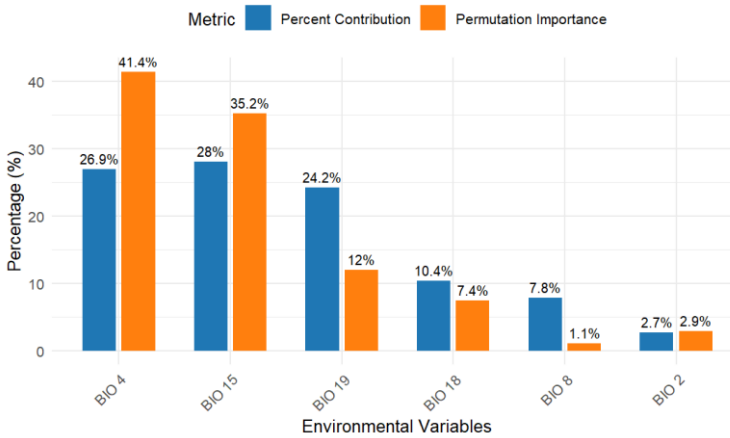
Analysis of environmental variable contributions utilising Jackknife methodology and permutation importance within the MaxEnt model revealed the differential roles of environmental factors in determining potential habitat suitability for Midas Cichlid throughout Indonesia. The variable BIO 15, representing precipitation seasonality, emerged as the dominant factor with a contribution of 28% and the highest permutation importance value of 35.2, indicating that seasonal precipitation patterns constitute the strongest predictor constraining the distribution of this invasive species. This finding suggests that Midas Cichlid exhibits considerable sensitivity to seasonal aquatic variability and habitat preferences intrinsically linked to hydrological cycles. The variable BIO 4, representing temperature seasonality, occupied the second position with a contribution of 26.9% and permutation importance of 41.4 (the highest among all variables), demonstrating that seasonal temperature fluctuations exert critical influence on species presence and habitat suitability. The variable BIO 19, representing cold quarter precipitation, contributed 24.2% with permutation importance of 12, indicating that specific seasonal precipitation patterns similarly influence species distribution.

These three variables collectively accounted for 79.1% of total model contribution, affirming that seasonal climatic variability, encompassing both precipitation and temperature seasonality, represents the primary environmental factors governing potential distribution of Midas Cichlid. Conversely, variables BIO 18 and BIO 8 demonstrated lower contributions (10.4% and 7.8% respectively), representing warmest quarter precipitation and mean temperature of the coldest quarter, whilst BIO 2 exhibited minimal contribution (2.7%), indicating that inter-monthly temperature variability is less determinative than long-term seasonal patterns. Jackknife analysis corroborated these findings: omission of BIO 15 resulted in marked decrease in regularised training gain, as did removal of BIO 4 and BIO 19, indicating that these three variables contain unique, non-redundant information in predicting species presence. The ecological implications of these findings suggest that Midas Cichlid exhibits strong niche specialisation towards climatic conditions exhibiting particular seasonal patterns, plausibly related to food availability, reproductive cycles, and optimal physiological conditions for survival and recruitment. Regarding invasive species management, these findings underscore the importance of monitoring changes in seasonal climatic patterns within Indonesian aquatic systems, particularly in zones of high suitability, as intensification or alteration of seasonal precipitation and temperature patterns may modify

habitat suitability and expansion potential. Consequently, adaptive management strategies must incorporate projections of future climatic change to remain effective in controlling this invasive species.



**Fig 4.** Graph of environmental variable contributions.



**Fig 5.** Percent contribution of variables.

### 3.5 Response curve analysis of environmental variables

Species response curves illustrating the relationship between each environmental variable and the probability of Midas Cichlid presence (cloglog output) reveal the detailed ecological niche preferences of this species. Variable BIO 2 exhibits a Gaussian-shaped curve with a peak at 8-9°C, achieving maximum cloglog output of approximately 0.9, indicating that Midas Cichlid favours environments characterised by moderate diurnal temperature ranges without extreme fluctuations. Species occurrence declines considerably at excessively low diurnal temperature ranges (< 6°C) or excessively high ranges (> 11°C).

Variable BIO 4 displays a symmetrical Gaussian curve peaking within the range of 40–60°C standard deviation, demonstrating that Midas Cichlid exhibits highly specific preferences for moderate to high seasonal temperature variability, with maximum occurrence probability (cloglog output ~0.9) within this range and marked decline at both extremes of the spectrum. This pattern indicates that the species functions as a specialist regarding seasonal temperature dynamics, requiring measured seasonal temperature fluctuations to sustain its life cycle.

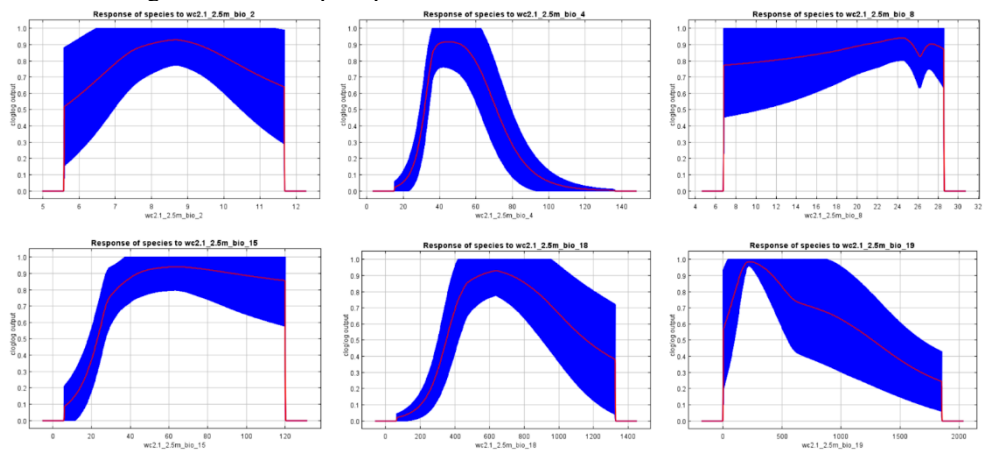
Variable BIO 8 demonstrates a gradually ascending curve from 8°C to approximately 26°C, with cloglog output progressively increasing with warmer temperature conditions,

reaching a plateau of approximately 0.9 at 26–28°C before declining sharply. This pattern indicates that Midas Cichlid is thermophilic, with optimal habitat values occurring at water temperatures of 26–28°C during the wet season, and occurrence becoming markedly rare at temperatures below 8°C. These findings align with the species' geographic origin in the warm tropical freshwater systems of Central America.

Variable BIO 15 presents a steeply ascending sigmoid curve between values of 20–60, with cloglog output rising from approximately 0.1 to approximately 0.95, demonstrating strong preference for regular and variable seasonal precipitation patterns. At values below 20 (precipitation distributed evenly throughout the year), species occurrence is minimal, whereas at values above 60 (high seasonal precipitation variability), the species achieves optimal probability. This indicates that the species requires pronounced seasonal patterns to optimise its life cycle dynamics.

Variable BIO 18 exhibits a broad unimodal curve with a peak between 600–900 mm, achieving maximum cloglog output of approximately 0.95, declining at substantially higher or lower precipitation values. This pattern reflects species preference for moderate warmest quarter precipitation, indicating sensitivity to extreme seasonal rainfall conditions.

Variable BIO 19 displays an asymmetrical unimodal curve with a broad peak between 300–800 mm, achieving maximum cloglog output (approximately 1.0) within this range and declining rapidly at precipitation below 100 mm or above 2,000 mm. This reveals that Midas Cichlid achieves optimal conditions in environments with moderate coldest quarter precipitation, with minimal occurrence under extremely arid or extremely wet conditions, demonstrating intolerance to precipitation extremes.



**Fig 6.** Species response curves.

## 4 Discussion

### 4.1 Biological Characteristics Facilitating Invasive Success

*Amphilophus citrinellus* has an anatomical structure optimised for opportunistic predation, including strong jaws with sharp teeth, specialised pharyngeal jaws for crushing mollusc shells and small fish bones, and a robust benthopelagic body (maximum 24.4 cm SL) [3, 12, 13, 14]. This morphology facilitates lepidophagy (fish scale eating) and selective piscivory towards native juvenile species, as evidenced by stomach content analysis with a frequency of occurrence (FO) of fish scales reaching 57% and vertebrate prey 6% (n=35). As

observed in invasive specimens in Malaysian agroecosystems that prey on *Betta imbellis* and frogs of the Dicroglossidae family [3].

As further evidence, the number of gill rakers in *A. citrinellus* is relatively low, typically 12–18 per first gill arch in wild populations in Nicaragua and Costa Rica, reflecting an adaptation for low filtration and processing of large prey. The distribution of *A. citrinellus* in Indonesia (e.g., Ir. H. Djuanda Reservoir, Lake Batur, Jembatan 12 Bangka River) [8, 11, 15] strongly correlates with bioclimatic variables representing optimal conditions in the native range (Lakes Nicaragua-Managua: 24–28°C, pH 7–8, low dissolved oxygen tolerance). Variables Bio2, Bio4 and Bio8 reflect tolerance to daily (8–12°C) and seasonal temperature fluctuations consistent with high-temperature habitats such as Lake Batur (station 1: high *Azolla pinnata* coverage) [8].

Midas Cichlid is found in Seberang Perai Tengah, Penang, Malaysia in areas ecologically associated with rheophilic-ricefield ecosystems [3]. Its presence increases the risk of competition for food and space with the native species in the area, *Pristolepis fasciata*. Areas with flowing rice field irrigation systems are commonly found in regions with high suitability indices, such as Java and Bali. Bio15, Bio18, and Bio19 indicate a preference for rheophilic-ricefield ecosystems with variable rainfall (1,500–3,000 mm/year), which supports year-round spawning (fecundity 300–1000 eggs/female) [13]. Observations at invaded locations confirm this suitability, namely at Djuanda Reservoir (elevation 1,000 m asl, temp. 24–27°C) and Bangka Island (tropical river), showing negative allometric growth ( $b = 2.60$ ) and condition factor ( $K_n = 1.04$ ) indicative of successful adaptation despite food-scarce conditions. These bioclimatic variables proxy represent critical parameters of Indonesian freshwater systems, where Bio2/Bio4 influence dissolved oxygen (DO) through diurnal heating. Under these conditions, DO can drop to  $<4$  mg/L at temperatures  $>28^\circ\text{C}$ , but *A. citrinellus* is tolerant via bimodal respiration. Bio8 correlates with primary productivity, i.e., high chlorophyll-a in eutrophic reservoirs, supporting an aufwuchs-dominant juvenile diet, while Bio15/Bio18/Bio19 predict flushing rates that facilitate larval dispersal. This niche model, validated with occurrences data (GBIF: 20+ records Indonesia), shows 80–90% overlap with invaded sites, emphasising the potential spread to high-risk reservoirs.

## 4.2 Documented Ecological and Biodiversity Impacts Leading to Community Structure Alteration

The Midas cichlid occupies a mid-to-upper trophic level ( $TL = 3.5 \pm 0.47$  SE) as an opportunistic predator that feeds on aquatic invertebrates, small fish, and small vertebrates, as documented in global ecological databases. This trophic position is corroborated by food item analyses comprising zooplankton, mollusks, earthworms, and small fish, which further supports its dominance in various invaded aquatic ecosystems across Southeast Asia [3]. This population dominance is clearly evident in Lake Batur (Bali), where the species accounts for 60% of the total fish biomass, disrupting the balance of endemic communities through competition and predation. The conservation implications become considerably acute when considering species-level vulnerability within these potential invasion zones [8]. In Jembatan 12 River, Bangka Belitung, where seven endemic freshwater fish species occur, several maintain Critically Endangered (CR) status including *Betta burdigala*, *Betta schalleri*, and *Betta chloropharynx*. These small endemic fishes, with body lengths of merely 3–12 cm, constitute primary predation targets for *A. citrinellus*, which attains lengths to 38 cm and weights approaching 1.2 kg [11]. Direct predation may result in dramatic population declines and local extinction of these already-threatened species.

Similarly, in the Ir. H. Djuanda Reservoir (West Java), *A. citrinellus* dominated the catch (460 out of 657 individuals), exhibiting a positive allometric growth pattern and high fecundity (300–1000 eggs/female), which accelerates population expansion [13]. Similar

reports from Laguna de Bay (the Philippines) highlight the potential for the competitive exclusion of native species, while in Malaysian rice paddies, predation on *Betta imbellis* and Dicroglossidae frogs confirms a direct threat to local biota [3]. In Singapore, their presence in urban stormwater ponds and concrete canals demonstrates adaptation to artificial habitats, implying a higher risk of broader dispersal.

The rapid reproductive capacity, characterized by a population doubling time of 1.4–4.4 years, exacerbates the invasion by establishing stable feral populations, as observed in both reservoirs and rice paddies. This threat is particularly acute for small-sized endemic species with lower trophic levels ( $TL < 3.0$ ), such as *Betta burdigala* (peat swamp habitat, primary invertebrate diet), which are highly vulnerable to size-specific predation and resource competition. Empirical evidence from invaded sites confirms alterations in community structures: a decline in native species abundance, simplification of trophic chains, and the potential loss of ecosystem functions. Consequently, preventive and curative management interventions are imperative to avert irreversible damage to local biodiversity [8, 12].

### 4.3 Spatial Distribution Predictions and Conservation Implications

MaxEnt analysis indicates that the potential distribution of the Midas cichlid encompasses southern East Java from Banyuwangi to Pacitan, and nearly the entire aquatic systems throughout Java, Bali, and Lombok. Limited potential areas exist in South Kalimantan and Central Kalimantan, particularly within and surrounding Sebangau National Park. Throughout Sulawesi, the potential distribution extends across the Central, Southeast, and South Sulawesi provinces, including adjacent small island aquatic systems such as Buton, Muna, and Kabaena Islands. In Papua, the potential distribution has been identified in Jayapura, Teluk Bintuni Regency, and Fak-Fak Regency. Distribution modelling predictions indicate that *Amphilophus citrinellus* has the potential to expand not only along the main Java-Sumatra-Kalimantan corridor but also into small islands with a high suitability index in eastern Indonesia, including Taliabu, Capalulu, Kei Kecil, and Kei Besar. The mapped potential areas exhibit climatic conditions analogous to Midas cichlid habitats in previously documented aquatic regions, characterized by specific environmental parameters including precipitation seasonality (BIO 15) and temperature seasonality (BIO 4). Given these environmental correspondences, further empirical research should be conducted within the potential distribution areas delineated by MaxEnt analysis to confirm *A. citrinellus* presence and facilitate timely management interventions prior to population establishment.

Connectivity between high-suitability islands and the global ornamental fish trade is highly likely to be amplified by the development and operation of new transportation infrastructure, specifically the airports in Taliabu and Capalulu, which effectively creates a "trade bridge" through the increased mobility of humans and live goods. Invasion ecology literature consistently demonstrates that the expansion of air and maritime transportation networks is positively correlated with the introduction frequency of non-native aquatic species via the ornamental fish trade, aquaculture, and both intentional and accidental releases. The global ornamental fish market is recognized as a primary vector for the dispersal of Neotropical cichlids into Asia, the Americas, and Oceania, frequently through complex supply chains that encompass exporters, importers, wholesalers, and local retailers operating in the vicinity of airports and seaports. Airports on small islands shorten logistical routes at the local scale; this reduces transportation costs and increases trade volumes. This combination, if not counterbalanced by stringent quarantine systems and regulations, can significantly elevate propagule pressure and the probability of invasive population establishment. In the ecologically isolated context of Taliabu and Capalulu, a successful invasion by the Midas cichlid into freshwater ecosystems would be highly detrimental due to

the absence of natural recolonization pathways and high levels of endemism, meaning a single introduction event could result in irreversible ecological and evolutionary impacts.

The policy implications of these findings demand an explicit, risk-based conservation and socio-economic approach. From a conservation perspective, islands with a high suitability index and planned airport developments must be prioritized as stringent biosecurity zones that integrate ornamental fish trade regulations (invasive species blacklists, business licensing, and the prohibition of releases), quarantine infrastructure at airports and seaports, as well as protocols for early detection and rapid response to the first occurrence of the Midas cichlid in local freshwater systems. Socio-economically, while airport construction and trade intensification open opportunities for local economic growth through tourism and ornamental fishery commodities, these benefits could potentially be negated by long-term external costs in the form of freshwater ecosystem service degradation, the loss of local fish stocks that support subsistence fisheries, and the erosion of cultural identities associated with endemic species. Therefore, an integrative policy framework is required that combines invasive risk assessments within infrastructure planning, incentive schemes for businesses to adopt low-risk trade practices, local community involvement in monitoring and reporting, and financing mechanisms (e.g., environmental service fees or biosecurity levies) to support long-term monitoring and restoration actions. This approach enables the achievement of a balance between the economic utilization of new infrastructure and the protection of the unique biodiversity of Indonesia's small islands, which are vulnerable to non-native fish invasions.

## **5 Conclusion**

This study shows that the Midas Cichlid has spread widely across various large islands in Indonesia since it was first introduced through the ornamental fish trade in the 1990s. Spatial modelling results confirm that the characteristics of Indonesia's tropical waters, with warm temperatures throughout the year, provide ideal conditions for the massive growth of this invasive species population. The identification of areas with a high risk of colonization is a key finding in this study for mapping the dynamics of the species' spread in freshwater ecosystems. Validated presence data from 19 locations provides a strong basis for analyzing the potential for expansion on a national scale. These findings are expected to serve as an important reference for relevant authorities in designing strategies to prevent and manage the ecological impacts caused by this fish. Overall, this study emphasizes the urgency of continuous monitoring of the presence of alien species in Indonesian waters to preserve local biodiversity.

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