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Resilience of *Mystacoleucus padangensis*: rediscovery, growth patterns, and conservation strategies in Lake Toba, North Sumatra

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Abstract. *Mystacoleucus padangensis* was introduced to Lake Toba in 2003 and thrived as a key fishery species until 2013. However, between 2014 and 2016, its population declined drastically, likely due to overfishing and competition with the invasive glassfish (*Parambassis siamensis*), leading to its presumed extirpation. Surprisingly, our ichthyofauna surveys in April and December 2024 revealed the species' persistence in the lake. Specimens were collected using cast nets and electrofishing in littoral zones and inlets, with individuals measuring 75–156 mm in length and weighing 3.78–39.48 g. The species was recorded in six of the seven regencies surrounding Lake Toba, with the highest catch per unit effort (CPUE) observed in the inlets of Toba and Simalungun regencies. The length-weight relationship followed an isometric growth pattern ($W = 0.000005 L^{3.1206}$, $R^2 = 0.98$), and the condition factor (K) across five size groups averaged 0.85–1.04. These findings indicate that *M. padangensis* could be rehabilitated as a fishery resource, supported by available habitat niches and phytoplankton-based food sources. Conservation strategies, including restocking programs, control of invasive alien species (e.g., *Amphilophus citrinellus*), and protection of critical inlet rivers, are recommended to restore this ecologically and economically important fish population.

1 Introduction

Lake Toba, the world's largest volcanic lake, spans 100 km in length and 30 km in width, with a maximum depth of 505 meters. It is located in the heart of North Sumatra, Indonesia [1, 2]. The lake hosts a diverse array of fish species, ranging from endemics such as *Neolissochilus thienemmani* to introduced species like the nile tilapia (*Oreochromis niloticus*) [3]. Historically oligotrophic, Lake Toba began trending toward a mesotrophic

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state in the early 2000s [4] due to increased nutrient loading from human activities, which stimulated plankton growth. In 2003, the Indonesian Ministry of Marine Affairs and Fisheries introduced "bilih" (*Mystacoleucus padangensis*) from Lake Singkarak into Lake Toba in an effort to taking advantage of the abundant plankton and enhance fisheries [5, 6]. Locally, the fish is named "pora-pora" for its resemblance to *Puntius binotatus*. An initial release of approximately 3,000 broodstocks [5, 6] led to a rapid population expansion, with annual production reportedly reaching 45,000 tons by 2012 and significantly boosting the local economy [7]. However, within a decade, the population was believed to have crashed to the point of local extinction. A decline attributed to overfishing [8], destruction of spawning habitats [9], and competition with invasive species, particularly the glassfish (*Parambassis siamensis*) [10].

Contrary to this belief, our ichthyofauna surveys of Lake Toba in April and December 2024 successfully identified the presence of *Mystacoleucus padangensis* in several inlet areas. This paper presents these significant findings, confirming the species' persistence in the ecosystem. We detail its current distribution, growth patterns, and key environmental factors, and provide recommendations for conservation strategies to aid its population recovery.

2 Methods

2.1 Time and location

The ichthyofauna survey of Lake Toba was conducted during two distinct periods: April 24–28 and December 15–20, 2024. The study encompassed the lake's entirety, with sampling sites distributed across all seven surrounding regencies: Toba, Samosir, Humbang Hasundutan, North Tapanuli, Simalungun, Dairi, and Karo (Figure 1). Sampling efforts targeted both the open waters of Lake Toba and the various tributaries flowing into it. All collected fish specimens were subsequently transported to the Bio-Makro Laboratory at the Faculty of Fisheries and Marine Sciences, IPB University, for taxonomic identification and further analysis.

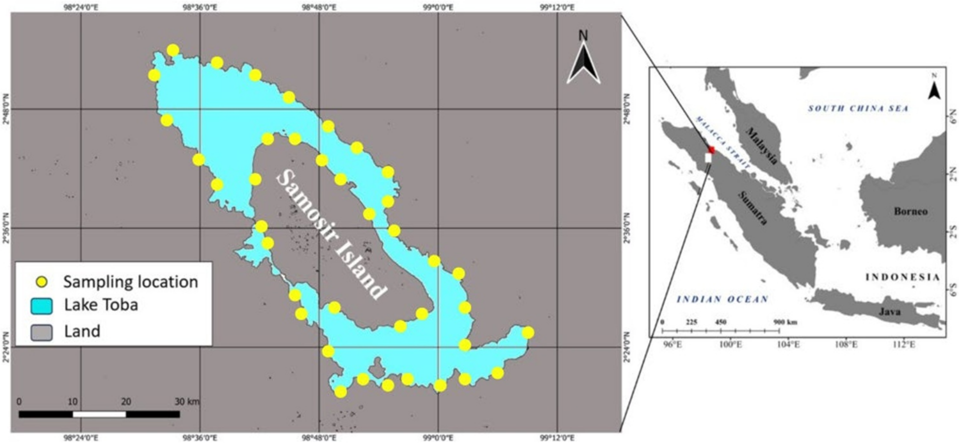

Figure 1. The ichthyofauna sampling location in Lake Toba.

2.2 Data collection

Prior to fish collection, key physical and chemical water parameters were measured in situ. These included temperature and dissolved oxygen (measured with a Lutron DO-5519 meter), pH (Lutron pH-208 meter), turbidity (Lutron TU-2016 meter), and conductivity and total dissolved solids (TDS) (using a Lutron YK-22CTA TDS meter).

Fish were sampled using two primary methods: cast nets and electrofishing. A monofilament cast net with a mesh size of 1 inch was deployed in the littoral zone of the lake and its tributaries. A standardized effort of ten cast net throws was performed per sampling station. Additionally, electrofishing was conducted in the tributary streams using a backpack unit operating at 12V and 9A. At each designated location in the tributaries, electrofishing was performed for three 15-minute sessions, covering a reach of approximately 150 meters.

All captured fish were first identified, photographed, and counted while alive. They were then preserved in a 10% formalin solution for subsequent detailed laboratory analysis. In the laboratory, each specimen was measured for total length (mm) using a digital caliper and weighed (g) using a precision digital scale.

2.3 Data analysis

The physical and chemical parameters of the water were analyzed descriptively. Fish abundance was quantified using the catch per unit effort (CPUE) method [11]. The unit of effort was defined separately for each gear type: one effort unit for the cast net was ten throws per station, and one effort unit for electrofishing was 45 minutes of active fishing time per sampling location. CPUE was calculated using the formula:

$$\text{CPUE} = \frac{C}{f}$$

where:
CPUE = catch per unit effort
C = catch (ind.)
f = Number of casts or fishing duration

The relationship between length and weight was used to determine the growth pattern of the fish. The slope parameter (b) from the length-weight regression ($W = aL^b$) serves as the indicator for this classification [12]. Growth is considered isometric when $b = 3$, indicating body shape remains proportional as the fish grows. A value of $b > 3$ indicates positive allometric growth (weight increases faster than length), while $b < 3$ indicates negative allometric growth (weight increases slower than length).

To statistically verify the observed growth pattern, a t-test was employed to determine if the estimated b value significantly deviated from the isometric value of 3. The hypotheses were defined as null hypothesis (H_0) if $b = 3$ (isometric growth), and alternative hypothesis (H_1) if $b \neq 3$ (allometric growth). The test was conducted at a 95% confidence level ($\alpha = 0.05$).

The calculated t-statistic was derived using the following formula:

$$t = |b - 3| / SE_b$$

Where:
b = the estimated slope coefficient from the regression, and
SE_b = the standard error of the slope coefficient.

The resulting t-value was compared to the critical t-value from the t-distribution table with n-2 degrees of freedom. If the calculated |t-statistic| > t-critical, the null hypothesis (H_0) was rejected, leading to the conclusion that the growth was significantly allometric. If the |t-statistic| ≤ t-critical, the null hypothesis was not rejected, supporting the conclusion of isometric growth.

The fish condition factor (CF) is calculated based on its growth pattern. In the case of isometric growth, the fish condition factor is determined using Fulton's condition factor formula. For fish exhibiting allometric growth patterns, the relative condition factor is calculated according to Le Cren's method [13].

$$CF = 10^5 / aL^b$$

$$CF_{rel} = W / aL^b$$

Where:
CF = Fulton condition factor
CF_{rel} = Relative condition factor
W = Body weight of individual fish (g)
L = Total length of fish (mm)
a and b = LWR regression coefficient parameters.

3 Result and discussion

3.1 Habitat and distribution

Mystacoleucus padangensis was found to inhabit both the littoral zone of Lake Toba and its various tributaries. Specimens were successfully captured in six of the seven surveyed regencies surrounding the lake. The specific collection sites were Bangkalu River-Lumban Silintong and Aek Alian, in Toba Regency; Aek Siparbue, Muara in North Tapanuli Regency; Sibea-bea and Siguluon-Simbolon River in Samosir Regency; Tongging in Karo Regency; Aek Horison-Haranggaol in Simalungun Regency; and Silalahi in Dairi Regency. The availability of suitable habitats that support the entire life cycle of fish determines their distribution and abundance in the lake [14].

The physico-chemical parameters of the habitats where *M. padangensis* was collected are summarized as follows (presented as range): water temperature 25.8–28.2 °C, dissolved oxygen 5.4–8.37 mg/L, pH 5.77–7.30, conductivity 148.3–155.3 µS/cm, turbidity 0–4.53 NTU, and total dissolved solids (TDS) 99.4–156.1 mg/L. The physical and chemical conditions of Lake Toba remain suitable for the survival of *M. padangensis* [15, 16].

3.2 Catch per unit effort, fish growth and condition factor

The catch per unit effort (CPUE) for *Mystacoleucus padangensis* exhibited considerable variation across the study locations, ranging from 1 to 23 individuals per unit effort. The highest CPUE value (23 individuals/effort) was recorded at the Bangkalu River site in Lumban Silintong, Toba Regency. This was followed by a CPUE of 18 individuals/effort at the Aek Horison site in Haranggaol, Simalungun Regency. At the remaining sites across other regencies, CPUE values were considerably lower, ranging between 1 and 7 individuals per effort.

These findings indicate a promising recovery of the *M. padangensis* population within the Lake Toba ecosystem, with the largest and most robust populations concentrated in the

Toba and Samosir Regencies. This recovery is likely facilitated by the presence of optimal environmental conditions in these areas, particularly suitable habitats in the tributaries for spawning and nursery [17], coupled with an abundant supply of food resources, primarily plankton (phytoplankton and zooplankton) [18].

Due to the limited sample size (n = 51), all specimens of *M. padangensis* were pooled into a single dataset to analyse the overall growth pattern within Lake Toba. The length-weight relationship was determined to be $W = 0.000005 \times L^{3.1206}$ ($R^2 = 0.9837$; Figure 2). A t-test was conducted to determine if the slope (b = 3.1206) significantly deviated from the isometric value of 3. The results indicated that the calculated t-value was less than the critical t-value ($\alpha = 0.05$), leading to a failure to reject the null hypothesis (H_0: b = 3). This confirms that *M. padangensis* in Lake Toba exhibits isometric growth ($b \approx 3$). Isometric growth denotes a proportional increase in body weight with increasing length, which is considered the ideal growth model [12]. A previous study conducted when this fish was still abundant in Lake Toba during 2012-2013 showed that its growth pattern was positively allometric (b = 3.31) [19].

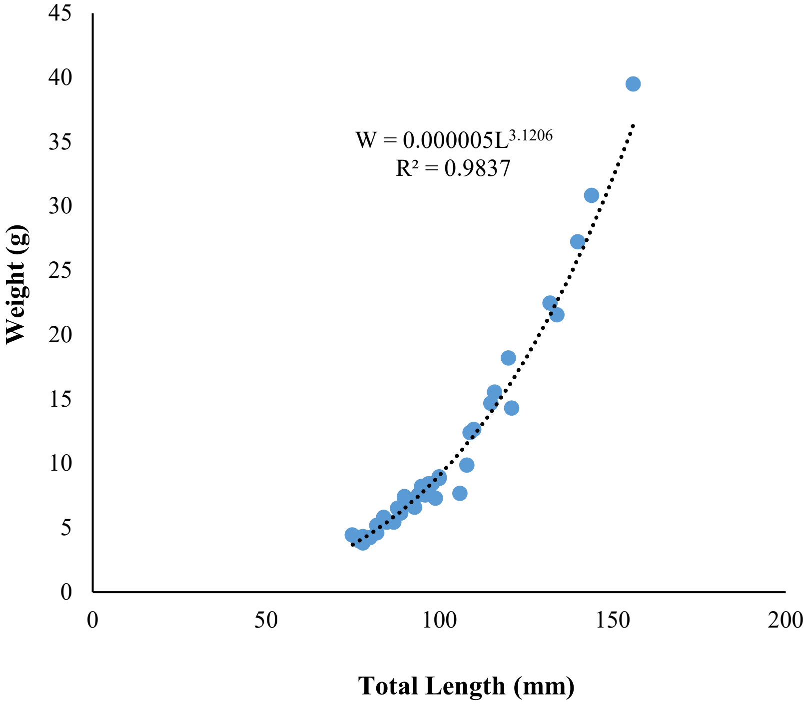

Figure 2. Length-weight relationship of *Mystacoleucus padangensis* in Lake Toba.

The condition factor (CF), or ponderal index, is a valuable metric for assessing the overall well-being of fish, reflecting their physiological state, survival capacity, and reproductive potential. For *Mystacoleucus padangensis* in Lake Toba, the condition factor ranged from 0.85 to 1.04 across the sampled population. A positive trend was observed, whereby the average condition factor increased with the total length of the fish (Figure 3). The highest mean condition factor was recorded in the largest size cohort (143–159 mm). Values approximating 1 across all size groups indicate that the fish are in good health and exhibiting robust growth [16, 20]. This suggests that the environmental conditions within Lake Toba are favorable, providing adequate resources for development across all life stages.

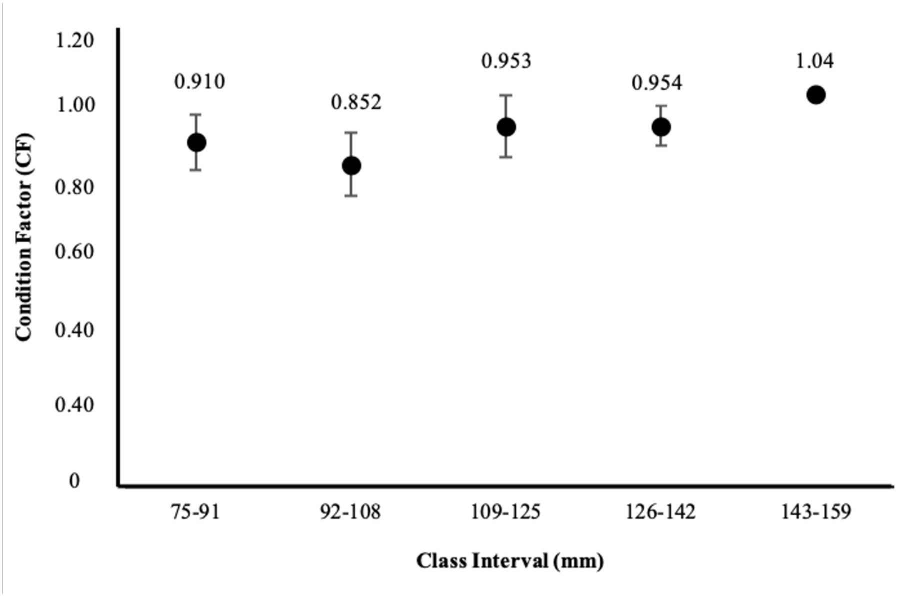

Figure 3. Condition factor (CF) by size group of *Mystacoleucus padangensis* in Lake Toba.

3.3 Restoration of *Mystacoleucus padangensis* in Lake Toba

The rediscovery of *Mystacoleucus padangensis* populations across six regencies surrounding Lake Toba, coupled with the observed isometric growth patterns and the presence of favorable environmental conditions—including suitable habitat niches and abundant phytoplankton-based food resources—collectively indicates a high degree of resilience in this species. These findings provide compelling evidence that the *M. padangensis* stock in Lake Toba has undergone a successful natural recovery.

The precipitous decline of *Mystacoleucus padangensis* to near-extinction in Lake Toba between 2013 and 2016 is attributed to a confluence of anthropogenic pressures [8]. The primary drivers were intense overfishing, particularly targeting mature individuals migrating to spawning grounds in the lake's inlets, and significant degradation of these critical spawning habitats. A contributing factor was the population explosion of the invasive glassfish (*Parambassis siamensis*), which preys upon the eggs and larvae of *M. padangensis* [10]. A general deterioration of Lake Toba's water quality further exacerbated these pressures.

Given its demonstrated resilience and current signs of recovery, *M. padangensis* possesses significant potential for rehabilitation as a sustainable fishery resource, echoing its economic importance from the 2003-2013 period. To achieve this, a multi-faceted conservation strategy is essential, building upon past efforts and incorporating the following key actions:

1. Restocking programs: implementing scientifically guided restocking programs using hatchery-reared fry from genetically diverse broodstock to supplement wild populations.
2. Invasive species management: developing and executing a targeted management plan to control populations of invasive species, particularly the dominant and ecologically disruptive red devil (*Amphilophus citrinellus*).
3. Habitat protection: establishing formal protection for critical inlet rivers that function as essential spawning and nursery grounds for *M. padangensis*.

4. Pollution control: enforcing stringent regulations to reduce pollution from aquaculture net cages and land-based runoff to improve overall water quality [21]
5. Systematic monitoring: implementing a long-term, regular monitoring program for water quality parameters in both the lake and its inlet rivers, alongside monitoring fish population dynamics [22].
6. Co-management framework: developing and institutionalizing a collaborative co-management framework for the *M. padangensis* fishery that actively involves all relevant stakeholders, including government agencies, local fishing communities, traditional leaders, academic and research institutions, the private sector, NGOs, and consumers [23].

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