Advances in biomass estimation of Nile tilapia aquaculture with acoustic methods

Luis Lorenzo Carrillo La Rosa[1], Vicente Puig-Pons[2], Sergio Morell-Monzó[2], Isabel Pérez-Arjona[2], and Víctor Espinosa[2]

[1]Departamento Académico de Manejo Pesquero y Medio Ambiente, Universidad Nacional Agraria La Molina, Lima, Perú
[2]Instituto de Investigación para la Gestión Integrada de Zonas Costeras (IGIC), Universitat Politècnica de València, EPS Gandia, Gandia, Spain

Abstract: *Nile tilapia (Oreochromis niloticus) is one of the most farmed fish species in the world with more than 5 million tons per year and is expected to continue to grow in the future. Traditional size monitoring and biomass estimation focuses on catch-and-release sampling methods. Acoustic methods have proven to be a potential tool for aquaculture monitoring. However, scientific echo sounders remain unfeasible in aquaculture due to their high cost. This work shows progress towards monitoring the biomass of Nile tilapia under production-like conditions from lateral target strength (TS) with a low-cost echo sounder. First, a biometric length-weight model was fitted from real specimens. Then, Biosonics DT-X echo-sounder with a single beam transducer operating at ~200 kHz was employed. The performance in estimating the average length through TSmax and TSmean was assessed for 8 size groups (from 14.1 to 43.7 cm) obtaining a* $R^2 > 0.9$*. These results are promising and provide an approach to the use of low-cost methods for biomass monitoring in aquaculture.*

Keywords: *underwater acoustics, lateral target strength, Oreochromis niloticus, single-beam echosounder*

1. INTRODUCTION

Nile tilapia (*Oreochromis niloticus*) is one of the most widely farmed fish species globally due to its fast growth rate, adaptability to various production systems, and high market demand. According to the Food and Agriculture Organization (FAO), global Nile tilapia production reached 5.3 million tons in 2024 [1]. Its rapid growth necessitates regular monitoring of key parameters such as body length, weight, and stocking density to ensure optimal farming performance. In recent years, video-based systems have been increasingly applied to estimate fish length and support a range of aquaculture management tasks. However, these systems often face limitations under poor visibility conditions. In this context, active acoustic systems have emerged as a promising non-invasive alternative for monitoring fish growth in aquaculture.

A growing body of research has explored the use of acoustic techniques for fish monitoring in cages and tanks [2,3,4]. These studies have demonstrated that target strength (TS)—defined as the amount of acoustic energy backscattered by an individual fish [5]—can be correlated with fish length when measured from different orientations (ventral or lateral). The backscattered TS signal depends on multiple factors, including fish size, the presence or absence of a swim bladder, and the orientation of the fish relative to the transducer.

The work [6] showed that a reliable relationship between TS and fish length can be established for Nile tilapia using a scientific echosounder. In their study, tilapia specimens of varying sizes were suspended in a laboratory tank, allowing for controlled measurement conditions. While scientific echosounders can compensate for TS variability due to the fish's position within the acoustic beam, their high cost and complexity limit their operational feasibility for routine use in commercial aquaculture.

In this study, we investigate the relationship between lateral TS, fish length, and weight in Nile tilapia (grey tilapia) using a single-beam echosounder operating at ~200 kHz. Unlike previous studies with restrained fish, our experimental setup involved freely swimming individuals, providing conditions more representative of production environments. The Biosonics DT-X echosounder is qualified as a scientific system, but we limited its performance by using a single beam transducer that was pre-calibrated. This configuration can be replicated with cost-effective quantitative echosounders and offers a significantly lower-cost alternative to scientific systems, thereby enhancing the potential for broader adoption in commercial tilapia farming.

2. DATA AND METHODS

2.1. Biometric measurements and relationships

Biometric data were collected at the Fish Research Center (Centro de Investigación Piscícola, CIMPIS) of Universidad Nacional Agraria La Molina, located in Lima, Peru (12°05′03″ S, 76°56′44.8″ W), over a 13-month period from December 2018 to December 2019. The measurements were conducted in a concrete pond measuring 4.0 × 4.0 × 1.5 m.

A total of Oreochromis niloticus specimens with total lengths (TL) ranging from 13 cm to 44 cm were selected and divided into eight experimental groups. Within each group, the maximum deviation from the mean TL was restricted to ±2 cm to ensure homogeneity in body size. The number of individuals per group ranged from 6 to 20, depending on fish availability. A detailed summary of the group composition is presented in Table 1. Total length (L) was measured to the nearest millimetre using a fish measuring board (ichthyometer), and individual body weight (W) was determined using a digital precision scale.

Group	Fish number	Mean L [cm]	Min L [cm]	Max L [cm]	Mean W [g]
G1	20	14.1	13.0	15.0	47.0
G2	15	17.9	17.0	19.0	99.4
G3	14	21.5	21.0	22.0	179.9
G4	14	24.6	24.0	25.0	230.1
G5	6	30.3	29.0	31.0	540.0
G6	6	35.1	34.0	36.0	758.3
G7	6	40.8	40.0	41.5	1383.3
G8	6	43.7	43.0	44.0	1445.8

Table 1. Data summary of each size group obtained.

Our previous results presented in [7] showed the relationship between Lt (total length) and Ls (standard length or fork length) and weight for this population of *Oreochromis niloticus* (Figure 1). We define the following biometric models: $W = 0.0265 \cdot Lt^{2.8465}$ and $W = 0.5123 \cdot Ls^{2.81193}$ with determination coefficients (R^2) of 0.982 y 0.977 respectively. Therefore, we decided to use Lt as a measure of length (so in this study L = Lt).

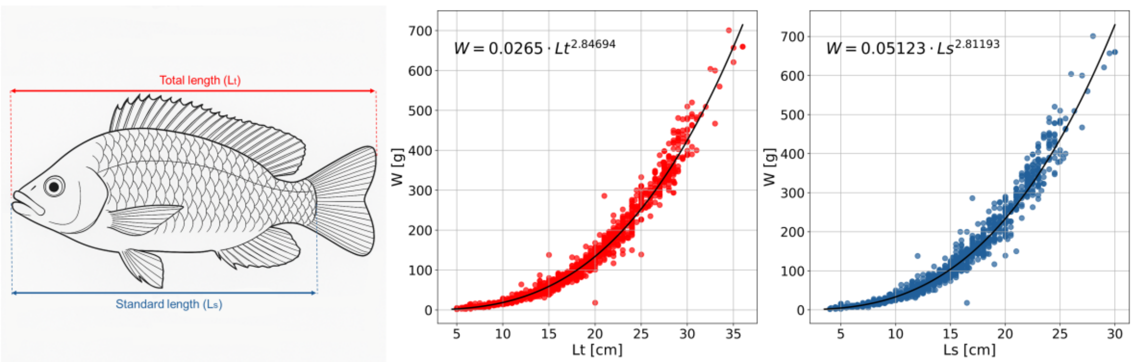

Fig.1: Length-weight relationships for Nile tilapia (Oreochromis niloticus) described in Carrillo La Rosa et al. 2025.

2.2. Acoustic data collection

Acoustic measurements were conducted using a BioSonics DT-X echosounder equipped with a single-beam transducer operating at 201 kHz. The transducer had a nominal beam width of 9.9° and was mounted horizontally at one end of the pond, such that the acoustic beam was directed parallel to the water surface. This configuration allowed for the acquisition of lateral target strength (TS) measurements, providing insight into fish orientation and behaviour under conditions similar to those in production environments.

The acoustic system was configured with a pulse duration of 0.1 ms, a ping rate of 5 pings·s^{-1}, and a source level of 202.3 dB re 1 µPa at 1 m. The receiver sensitivity was –64.9 dB. These settings were selected to optimize the detection of individual fish targets while minimizing interference and multipath reflections. A summary of the system configuration is provided in Table 2.

For each size group, data were collected over 2 to 5 consecutive days, as detailed in Table 1. During acoustic sampling, fish swam freely within the pond, allowing for the observation of natural swimming behaviour and orientation within the acoustic beam. Data acquisition was performed using BioSonics® Visual Acquisition software. Recordings were recorded in 30-minute files to facilitate post-processing and analysis.

Special care was taken to minimize acoustic noise and unwanted reflections. Measurements were conducted under calm water conditions to reduce signal degradation due to surface turbulence or air bubbles. The choice of lateral orientation, although less commonly used than the ventral approach, was made to reflect the typical horizontal posture of tilapia in shallow water environments and to evaluate the feasibility of TS-based length and weight estimation under realistic aquaculture conditions.

2.3. Acoustic data analysis

Acoustic data were processed and analysed using Sonar5-Pro software [8]. Echograms were transformed and filtered using a –95 dB threshold to enhance target image quality and reduce background noise. Given the use of a single-beam transducer, the 2D single echo detector (SED) algorithm was applied to detect individual fish echoes.

The validated TS data from Sonar5-Pro were exported for statistical analysis using Statgraphics Centurion XIX. Relationships were evaluated between both the mean and maximum TS values and the total length (L) of the fish. A logarithmic linear regression model was applied, following the commonly used form:

$$TS = a \cdot \log(L) + b \quad (1)$$

where a represents the slope, b is the intercept, and TL is the total length in centimetres. Although it is standard practice to apply a fixed slope (typically around 20), in [9] it was shown that allowing both a and b to vary provides better fits for TS–L relationships. In this study, both parameters were estimated empirically based on lateral TS measurements and the biometric data collected for each group.

3. RESULTS AND DISCUSSION

The results obtained are summarized in Table 2. For each size group, between 1,402 and 8,696 high-quality echo traces were manually isolated and retained for analysis. The lowest number of traces was recorded in the smallest group which is Group 1 (mean TL=14.1 cm), likely due to weaker echo returns and lower detectability. Conversely, the highest number of traces was obtained for Group 3 (mean TL=21.5 cm), which yielded more consistent and detectable signals.

For each group, the mean, median, and standard deviation were computed from the distributions of both mean TS and maximum TS. Mean TS values ranged from –42.2 dB to –34.8 dB, while maximum TS values ranged from –41.0 dB to –32.0 dB (Table 2).

There is a clear positive correlation between the average TS levels and the average length of the group. Figure 2 shows the scatterplot of the averaged TS (both TS_{mean} and TS_{max}) and the averaged L of each group and the regression analysis. Both regression models showed $R_2 > 0.90$ indicating strong predictive power.

Group	Mean TL [cm]	TS_{mean} (dB)			TS_{max}(dB)			Number of traces
		Average TS_{mean}	Median TS_{mean}	Standard deviation	Average TS_{max}	Median TS_{max}	Standard deviation	
1	14.1	-44.2	-44.0	3.4	-41.3	-41.0	3.5	1402
2	17.9	-43.7	-43.5	3.6	-40.8	-40.6	3.8	2240
3	21.5	-41.7	-40.6	5.7	-39.6	-38.6	6.0	8696
4	24.6	-41.5	-41.4	3.4	-36.9	-37.1	3.7	1698
5	30.3	-38.6	-38.7	4.0	-36.4	-36.4	4.0	5088
6	35.1	-38.3	-38.5	3.4	-35.9	-36.3	3.7	2291
7	40.8	-34.9	-34.4	4.5	-32.5	-31.9	4.6	8612
8	43.7	-34.8	-34.7	3.8	-32.1	-32.0	3.8	5400

Table 2. Averaged TS_{mean}, TS_{max} and its standard deviation for each group size of Nile tilapia

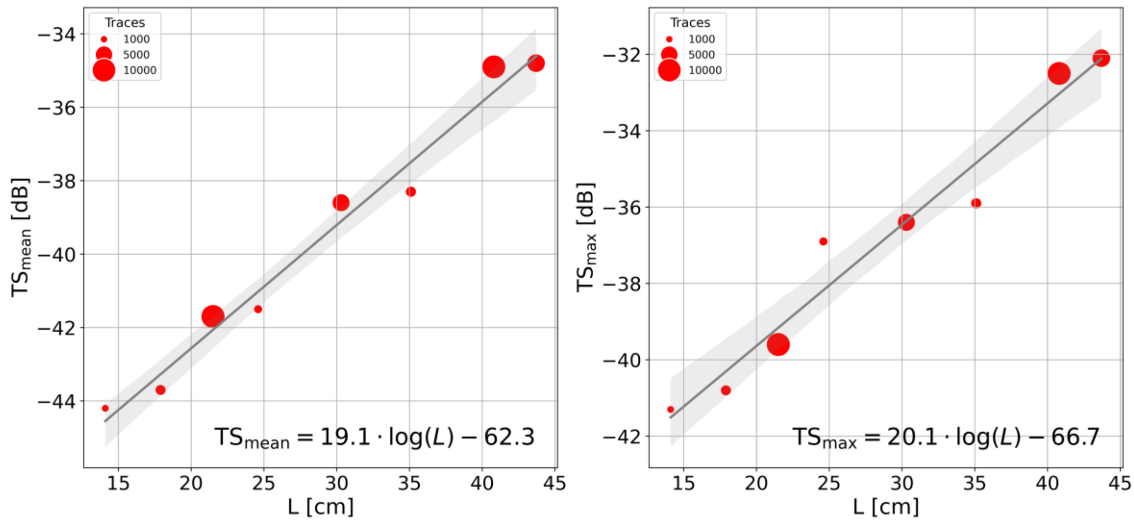

Fig.1: Regression analysis between the averaged TS_{mean} or averaged TS_{max} of each group and the averaged L. The size of the dots is proportionally large to the number of traces in that group. The grey region represents the 95% confidence interval. (left) shows the relationship between TS_{mean} and L with an R^2 of 0.94. (right) shows the relationship between TS_{max} and L with an R^2 of 0.91.

The results obtained are promising and confirm a strong predictive power of the mean length of a Nile tilapia population through the lateral target strength, especially through the TS_{mean}. This study should be complemented by direct estimation of weight through the TS to determine the biomass of the stock. Additionally, the results should be validated with simulations using 3D digital models of *Oreochromis niloticus'* swimbladder. This work provides the first experience in the estimation of TS vs L in free-swimming tilapia, which resembles real production conditions.

4. ACKNOWLEDGEMENTS

This study is part of the ThinkInAzul programme and was supported by MCIN with funding from European Union NextGenerationEU (PRTR-C17.I1) and by Generalitat Valenciana (GVA-THINKINAZUL/2021/009; Principal Investigator: V. Espinosa Roselló, Universitat Politècnica de València).

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