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PREDICTION OF ENVIRONMENTAL EXTERNALITY AND MONETIZATION OF ENVIRONMENTAL SERVICES FOR FISH PRODUCTION IN NEOTROPICAL LAKE

Moranne Toniato da Silva

Jaboticabal, SãoPaulo

2026

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SUMMARY

LIST OF ABREVIATIONS AND ACRONYMS

ADG – Average Daily Gain

ANA – National Water and Sanitation Agency (Agência Nacional de Águas e Saneamento Básico, Brazil)

ANOVA – Analysis of Variance

APHA – American Public Health Association

APP – Permanent Preservation Area

CICES – Common International Classification of Ecosystem Services

CONAMA – National Environmental Council (Conselho Nacional do Meio Ambiente, Brazil)

DO – Dissolved Oxygen

ECCp – Environmental Carrying Capacity based on Phosphorus

EC – Electrical Conductivity

ERF – Emissions Reduction Fund

ES – Ecosystem Services

ESC – Cultural Ecosystem Services

ESP – Provisioning Ecosystem Services

ESR – Regulating Ecosystem Services

ESS – Supporting Ecosystem Services

FAO – Food and Agriculture Organization of the United Nations

FCR – Feed Conversion Ratio

IMTA – Integrated Multi-Trophic Aquaculture

InVEST – Integrated Valuation of Ecosystem Services and Tradeoffs

JVI – Juvenile I

JVII – Juvenile II

MEA – Millennium Ecosystem Assessment

MRV - Monitoring, Reporting, and Verification

MWt – Market Weight

OECD – Organisation for Economic Co-operation and Development

P – Phosphorus

P_a – Phosphorus Released into the Aquatic Environment per Ton of Fish Produced

P_actual – Actual Phosphorus Release

P_avoided – Avoided Phosphorus Load

P_conv – Conventional Phosphorus Load Established by the Regional Environmental Authority

P_diff – Difference Between Conventional and Actual Phosphorus Release

P_released – Phosphorus Release per Ton of Fish Produced

PES – Payments for Ecosystem Services

PES_value – Reference Payment for Ecosystem Services Value

PF – Payment Factor

PRISMA – Preferred Reporting Items for Systematic Reviews and Meta-Analyses

REA – Regional Environmental Authority

REDD+ – Reducing Emissions from Deforestation and Forest Degradation

RSS – Residual Sum of Squares

SEC – Cultural Ecosystem Services

SEP – Provisioning Ecosystem Services

SER – Regulating Ecosystem Services

SES – Supporting Ecosystem Services

TEEB – The Economics of Ecosystems and Biodiversity

TGC – Thermal Growth Coefficient

TP – Total Phosphorus

Wt – Water Temperature

YSI – Yellow Springs Instruments

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DEDICATION

I dedicate this work to my beloved grandfather, Raul Rocha, whose memory accompanies me in every achievement. His presence remains alive in my heart.

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USE OF ARTIFICIAL INTELLIGENCE

In accordance with the *Guide for the Use of Artificial Intelligence in Undergraduate Education at UNESP* (Bego and Salvadeo, 2026), the author declares that generative artificial intelligence and writing-assistance tools were used during the preparation and revision of this dissertation.

OpenAI ChatGPT was used as a support tool for translating text from Portuguese into English; improving grammar, clarity, cohesion, concision, and academic style; assisting in the organization of sections and arguments; and suggesting alternative formulations. Grammarly was used to support spelling, grammar, punctuation, readability, and writing-style revision.

The artificial intelligence tools were not used as primary sources of scientific evidence and did not replace the author's intellectual contribution or scientific judgment. The research questions, methodological decisions, data collection, model selection, calculations, data analyses, interpretation of results, tables, figures, arguments, and conclusions were developed, reviewed, and validated by the author under the supervision of the advisor and co-advisor.

All artificial intelligence outputs were critically evaluated, edited, adapted, or rejected before incorporation into the dissertation. The author assumes full responsibility for the accuracy, originality, interpretation, and integrity of the content presented in this work.

The use of ChatGPT occurred through different model versions available on the web-based platform during the development of the dissertation; therefore, a single model version cannot accurately represent all interactions. Representative prompts included requests to translate passages into academic English, revise grammar and academic writing, improve clarity and cohesion, suggest alternative formulations, and assist in organizing sections without altering the scientific meaning of the original content.

GRAPHICAL ABSTRACT

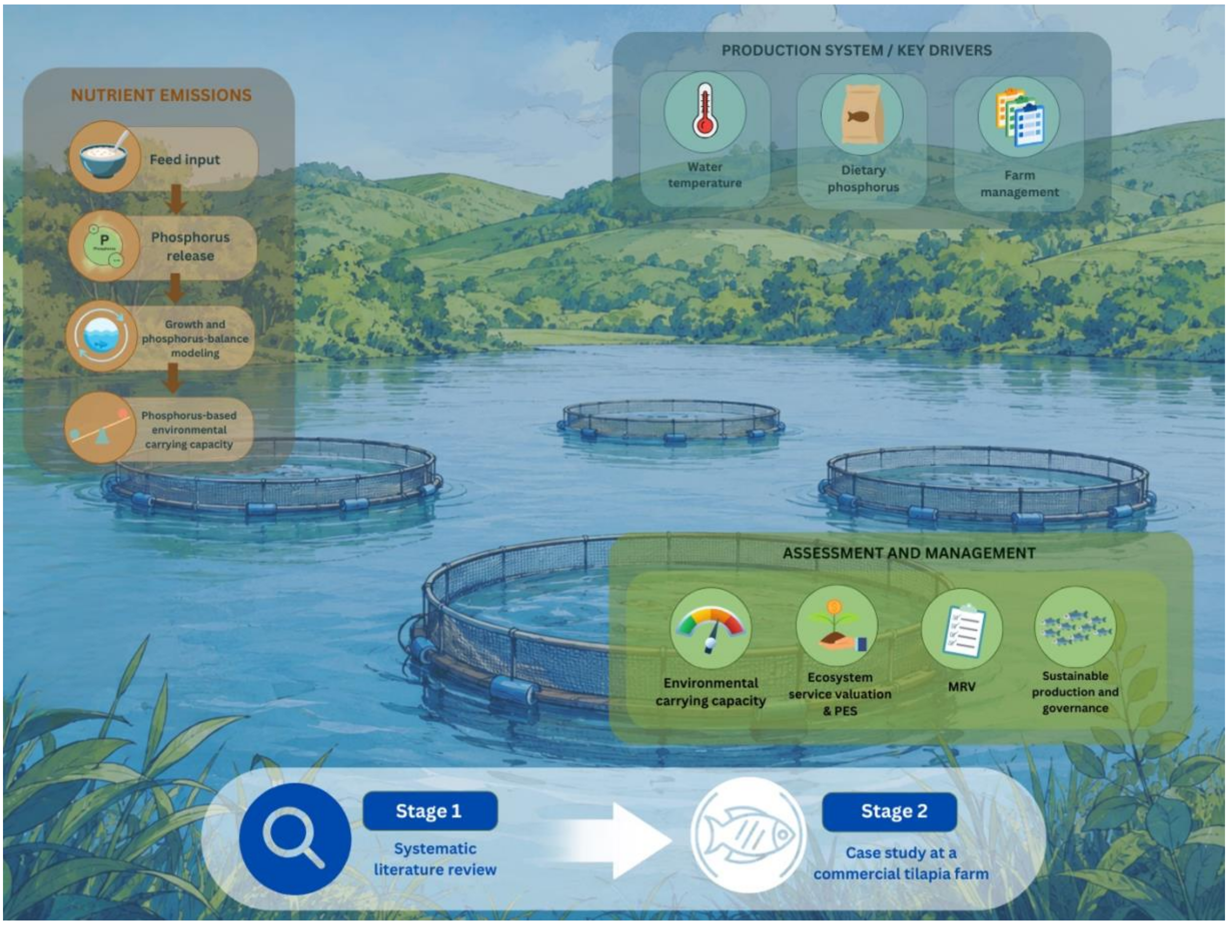

Figure 1. Conceptual framework linking nutrient emissions, production drivers, and environmental assessment and management in cage aquaculture. Source: Prepared by the author (2026).

GENERAL ABSTRACT

Economic instruments, including Payments for Ecosystem Services (PES), have been discussed as strategies for integrating environmental conservation with productive activities. However, operational frameworks connecting aquatic environmental indicators, production limits, and economic compensation remain poorly established in inland aquaculture. This dissertation was conducted in two complementary stages. The first consisted of a systematic literature review following PRISMA guidelines, focusing on environmental monetization, economic incentives, and PES applications in aquatic ecosystems. Analysis of 67 scientific studies showed a predominance of watershed-oriented initiatives and regulating ecosystem services associated with water quality and nutrient dynamics. Aquaculture was rarely incorporated into formal compensation arrangements, and recurring limitations involved baseline definition, additionality, governance, monitoring, conditionality, and standardization of environmental indicators. The second stage comprised an applied assessment of a commercial Nile tilapia (*Oreochromis niloticus*) cage-farming system in the Vale do Ribeira region, São Paulo State, Brazil. Production data from four monitored cages were combined with lake morphometry, hydrology, phosphorus-balance calculations, deterministic nutritional and thermal scenarios, and enterprise-budget analysis. Using an allowable phosphorus increment of 5 $mg \cdot m^{-3}$, the maximum modeled phosphorus-load limit for the lake was estimated at 4.67 kg $P \cdot year^{-1}$. Annualized production derived from the four monitored cages was approximately 1.85 $t \cdot year^{-1}$ and exceeded the modeled load limit under all evaluated scenarios. Temperature-related differences represented model outputs rather than experimentally measured effects. No scenario met the exploratory PES criteria at the annualized reference production. Potential eligibility occurred only after modeled production reductions, and the corresponding payments were insufficient to offset the associated economic losses. The findings show that phosphorus release per tonne of fish, total annual production, compatibility with the modeled load limit, and economic viability represent related but distinct management dimensions. The proposed framework should therefore be interpreted as an exploratory decision-support approach rather than as a validated PES mechanism or an operational compensation program.

Keywords: aquaculture sustainability, bioeconomy, ecosystem service valuation, environmental carrying capacity, Nile tilapia, ecosystem services.

GENERAL INTRODUCTION

Aquaculture has become one of the fastest-growing food-production sectors worldwide and supplies an increasing share of aquatic foods for human consumption. Although this expansion plays a strategic role in food and nutritional security, increasing production may also intensify environmental pressures associated with resource use, nutrient emissions, and changes in aquatic ecosystem functioning (Boyd & McNevin, 2015; Bohnes et al., 2019; Valenti et al., 2021; FAO, 2026). In continental aquatic systems simultaneously used for human consumption, agriculture, energy generation, recreation, and aquaculture, productive intensification may increase competition over water quality and the shared use of freshwater resources. Water, when managed as a shared natural resource, may present characteristics of a common-pool resource, including difficulties in excluding users and rivalry in resource use. These conditions may contribute to overexploitation and socio-environmental conflicts when appropriate governance mechanisms are absent (Ostrom, 1990).

In multiple-use aquatic systems, water quality alterations resulting from excessive nutrient inputs may simultaneously compromise economic activities and ecosystem services, intensifying disputes among productive sectors and freshwater users. International organizations have highlighted the increasing pressure on freshwater systems resulting from environmental degradation, unequal access, and competition among water uses. These pressures may intensify tensions among users and reinforce the need for governance instruments capable of integrating environmental conservation, production, and equitable access to freshwater resources (UNESCO, 2019).

Continental aquaculture represents both an opportunity for rural development and a potential source of environmental pressure, particularly in intensive farming systems associated with phosphorus and nitrogen emissions. Excessive nutrient discharge is associated with eutrophication, dissolved oxygen depletion, and freshwater-quality degradation, potentially compromising multiple uses of aquatic ecosystems (Boyd & McNevin, 2015).

In tropical regions, interactions among water temperature, fish metabolism, feed intake, nutrient retention, and seasonal hydrological variability may influence nutrient emissions and the assimilative capacity of freshwater systems. Under unfavorable environmental or management conditions, these interactions may increase the risk of nutrient accumulation, eutrophication, and reductions in environmental carrying capacity. Nile tilapia farming represents one of the most important segments of Brazilian aquaculture and illustrates the relationship between productive expansion and the need for appropriate environmental management (Bueno et al., 2015; Valenti et al., 2021).

High stocking densities and the intensive use of formulated feeds may increase phosphorus and nitrogen loads released into aquatic environments, making nutrient quantification essential for estimating environmental carrying capacity and defining production limits compatible with freshwater-quality objectives. From this perspective, the integration of environmental modeling with economic and farm-management analyses can support the development of more sustainable aquaculture management strategies (Engle, 2020).

Simultaneously, economic instruments have gained prominence as mechanisms capable of incorporating costs associated with environmental degradation, water pollution, and ecosystem service impairment into production systems and decision-making processes. Ecosystem-service monetization refers to the attribution of economic values to ecological functions and environmental benefits that are not fully represented in conventional markets. Payments for Ecosystem Services (PES), in turn, constitute institutional arrangements that operationalize such values through conditional compensation mechanisms involving ecosystem service providers and beneficiaries (Engel et al., 2008; Muradian et al., 2010; Wunder, 2015).

Environmental monetization therefore represents a broader valuation process, whereas PES corresponds to one of the main practical strategies for applying such values in environmental governance instruments and public policies. In Brazil, the establishment of the National Policy for Payments for Environmental Services through Federal Law No. 14,119 of 13 January 2021 created a national regulatory framework for the development of PES programs across different ecosystems and productive sectors (Brazil, 2021).

In 2026, Federal Decree No. 13,018 regulated the National Policy and the Federal Program for Payments for Environmental Services, further defining institutional, contractual, monitoring, and socio-environmental requirements for PES initiatives in Brazil (Brazil, 2026). Despite this institutional advancement, applications directed specifically toward aquaculture remain limited. More broadly, the PES literature identifies recurring challenges involving ecosystem-service measurement, the definition of verifiable indicators, environmental monitoring, conditionality, equity, and the inclusion of stakeholders in governance arrangements (Pascual et al., 2010; Salzman et al., 2018; Kaiser et al., 2021).

Recent studies demonstrate advances in the application of economic and financial instruments to coastal and marine ecosystems, particularly in relation to mangrove conservation, carbon benefits, ecosystem restoration, and blue-economy financing (Jakovac et al., 2020; Bennett et al., 2024). Conversely, the literature reviewed in this dissertation indicates that freshwater ecosystems and inland aquaculture enterprises remain less frequently addressed in environmental-incentive frameworks than coastal, marine, terrestrial, and watershed-conservation contexts. Economic valuation models, compensation mechanisms, and governance structures identified in recent literature represent relevant opportunities for adaptation and application in continental aquaculture systems.

This dissertation was organized into two complementary stages. The first comprised a systematic review of environmental monetization, economic incentives, and Payments for Ecosystem Services in aquatic ecosystems, with emphasis on conceptual, methodological, and governance limitations relevant to aquaculture. The second comprised an applied case study conducted at a commercial Nile tilapia farm in the Vale do Ribeira region, São Paulo State, Brazil. The applied assessment combined production data from four monitored cages, water-quality observations, lake morphometry and hydrology, phosphorus-balance calculations, deterministic nutritional and thermal scenarios, and enterprise-budget analysis.

The integration of the two stages allowed limitations identified in the international PES literature to be examined in an aquaculture case study. Rather than establishing an operational compensation mechanism, the applied chapter evaluated how modeled phosphorus-load reduction could be incorporated into an exploratory environmental and economic assessment. The approach distinguished reductions in phosphorus release per tonne of fish from total compliance with the modeled lake limit, economic viability, and the institutional requirements of a future PES arrangement.

5. CONCLUSIONS

Using an allowable phosphorus increment of 5 $mg \cdot m^{-3}$, phosphorus-based environmental carrying capacity for the rural lake was estimated at 4.67 kg $P \cdot year^{-1}$. Annualized production from the four monitored cages reached approximately 1.85 $t \cdot year^{-1}$ and exceeded the modeled phosphorus-load limit under every evaluated scenario. Depending on phosphorus released per tonne of fish, compatible production ranged from 0.22 to 1.26 $t \cdot year^{-1}$, while phosphorus-load utilization ratios at 1.85 $t \cdot year^{-1}$ ranged from 1.47 to 8.47.

Greater dietary phosphorus concentrations generally produced higher modeled release coefficients and lower compatible production. Within deterministic simulations, higher temperature inputs were also associated with increased phosphorus release in several nutritional scenarios. Such associations represent model outputs rather than experimentally demonstrated temperature effects because thermal conditions and simulated diets were not evaluated as independent farm treatments. Complete reporting of feed conversion, digestibility, phosphorus retention, and waste-partitioning parameters remains necessary for reproducing those estimates.

Dietary adjustment alone was insufficient to maintain annual phosphorus loading within modeled capacity. Feed composition, feed conversion, total feed input, harvested biomass, cycle frequency, and number of active cages must be considered together. Even scenarios with lower phosphorus release per tonne exceeded 4.67 kg $P \cdot year^{-1}$ at the annualized production of four cages. Simultaneous operation of all 34 installed cages would further increase nutrient loading under equivalent stocking and management conditions, although such production represented a hypothetical scaling exercise rather than observed farm output.

Mean total phosphorus remained below the reference value established for Class 2 lentic freshwater environments, but pH averaged below the regulatory range and dissolved oxygen during Juvenile I averaged below 5.0 $mg \cdot L^{-1}$. Mean values alone could not confirm regulatory compliance or exclude localized and cumulative effects near the cages. Water-column monitoring should therefore be complemented by individual-observation assessment, spatial sampling, sediment analysis, phosphorus fractionation, and evaluation of seasonal hydrological conditions. Stage-specific TGC values described fish growth during one monitored cycle and were not obtained through parameter calibration. Accordingly, they should not be extrapolated as validated growth coefficients for temperatures of 21, 25, and 29 °C. Additional production cycles and more frequent biometric observations would be required for temperature-dependent growth calibration and validation.

No scenario qualified for PES at 1.85 $t \cdot year^{-1}$ because annual phosphorus loading remained above modeled capacity. Four scenarios became potentially eligible only after production was reduced to between 0.87 and 1.26 $t \cdot year^{-1}$. Simulated payments ranged from R$3.33 to R$10.99 $year^{-1}$ and covered only a small portion of the economic loss associated with production adjustment. Fish sales covered variable costs in all evaluated conditions but did not recover allocated fixed costs. Net return under current monitored production was −R$17,573.12 $year^{-1}$, while environmentally adjusted scenarios produced net returns after PES between −R$18,479.53 and −R$19,085.91 $year^{-1}$. Therefore, under the adopted assumptions, the simulated payment was insufficient to make the required production adjustment economically viable.

Practical use of phosphorus reduction as an environmental-service indicator would require a verified baseline, defined payer and provider, locally supported valuation, monitoring procedures, independent verification, and contractual rules. Application to other cage-farming systems would also require new calculations using local production, feed composition, hydrology, morphometry, background water quality, and sediment conditions. Under those limitations, the approach may assist comparisons among production alternatives and identify situations in which phosphorus reduction, compliance with modeled capacity, and economic viability do not occur simultaneously.

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