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ANIMAL PRODUCTION

Food web and ecological models used to assess aquatic ecosystems submitted to aquaculture activities

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ABSTRACT: *Continental aquatic ecosystems play a fundamental role in economic and social development; however, they are vulnerable to environmental degradation due to the various stresses to which they are submitted. Aquaculture is among the main anthropic activities that influence these environments. Mathematical modelling of aquatic ecosystems performed using a set of computational tools allows simplified representation of environment regarding its biotic and abiotic components. Some of the most used techniques are: hydrodynamic modelling, focusing on the dispersion of nutrients; nutrient-mass balance modelling, especially phosphorus; bioenergetic modelling in animal production systems, with an estimate of the generation of residues in the environment by farmed animals; and trophic and ecological modelling, focusing on aquatic communities and their interactions. These techniques help understand changes caused by aquaculture systems in aquatic environments. In this way, it is possible to estimate the magnitude and extent of the impacts of these activities by simulating the possible environmental changes over time. It can be concluded that techniques involving mathematical modelling can provide relevant information for future impacts prediction on aquatic environments, promoting the management of water resources and their multiple uses.*
Key words: *ecosystem modelling, trophic models, aquaculture impacts.*

Modelos tróficos e ecológicos aplicados a avaliação de ecossistemas aquáticos submetidos à atividades de aquicultura

RESUMO: *Ecossistemas aquáticos continentais desempenham papel fundamental no desenvolvimento econômico e social, entretanto, são vulneráveis à degradação ambiental devido às diversas pressões a que estão submetidos. Entre as principais atividades antrópicas a interferir nestes ambientes, podemos destacar a aquicultura. A modelagem matemática de ecossistemas aquáticos permite a representação simplificada do ambiente, em seus componentes bióticos e abióticos, através de um conjunto de ferramentas computacionais. Neste contexto, entre as técnicas mais utilizadas estão a modelagem hidrodinâmica, com foco na dispersão de nutrientes; a modelagem do balanço de massa de nutrientes, em especial o fósforo; a modelagem bioenergética em sistemas de produção animal, com estimativa da geração de resíduos pelos animais de cultivo para o ambiente; e a modelagem trófica e ecológica, com foco nas comunidades aquáticas e suas interações. Estas técnicas auxiliam no entendimento das alterações provocadas por sistemas de aquicultura em ambientes aquáticos. Deste modo, é possível estimar a magnitude e extensão dos impactos destas atividades, simulando as possíveis alterações ambientais ao longo do tempo. Pode-se concluir que as técnicas envolvendo modelagem matemática podem produzir informações relevantes para a predição de impactos futuros sobre ambientes aquáticos, dando subsídios para a gestão de recursos hídricos e seus múltiplos usos.*
Palavras-chave: *modelagem de ecossistemas, modelos tróficos, impactos da aquicultura.*

INTRODUCTION

Mathematical modelling is one of the ways to understand the structure and functioning of aquatic ecosystems. It has been increasingly developed and widely used, especially in recent years (BUENO et al., 2017; HAAK et al., 2017; VASSLIDES et al., 2017; WHITE et al., 2017; ZHOU et al., 2017). In the last two decades, more than 100 mathematical models have been developed and applied in aquatic ecosystems (TROLLE et al., 2012). These models have dealt with simpler scenarios, such as modelling the transport of nutrients or aquatic populations, and complex scenarios, such as representing an entire ecosystem numerically.

Currently, the models continue to become increasingly detailed, allowing modelling, simulation, and prediction of a growing number of components and processes (ROBSON, 2014). The greatest challenge of the models applied to aquatic ecosystems has been to increase environmental resolution, i.e., the complexity of the processes and patterns that can be

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modelled. In general terms, there is a trend in the use of a few models (which have become consolidated in the literature) to the detriment of development and improvement of new models that are more complex (MOOIJ et al., 2010).

Mathematical modelling can be applied to predict changes in water quality along environmental gradients, aiding in the prediction of physical and chemical characteristics in water columns. CUNHA-SANTINO et al. (2017) created a model for modelling mass balance for 23 limnological variables in a system of six cascaded reservoirs. The authors reported that the system was able to decrease the concentrations of all variables by up to 87%. The retention potential may be very low for some reservoirs, depending mainly on factors such as dissolved oxygen concentration, light penetration, water velocity, stratification, height of water outlet, and epilimnion and hypolimnion depths. However, the evaluation made it possible to understand the means by which water quality was affected in each reservoir, and how the set of six environments behaved in the maintenance of water quality of the main river.

Most ecological models are rarely applied by a small part of the scientific community, and an even smaller fraction have access to the source code for possible contributions (TROLLE et al., 2012). In this context, we can mention some models that have stood out over the years, namely: (i) Hydrodynamic and/or water quality models, such as DYRESM/ELCOM/CAEDYM, DELFT3D, CE-QUAL-W2, and PROTECH; (ii) Mass balance models for phosphorus (DILLON & RIGLER, 1974; VOLLENWEIDER, 1975); (iii) Complex ecological models, such as Ecopath with Ecosim; (iv) Dynamic simulation models, such as STELLA and VISQ; and (v) Bioenergetic models, such as Fish-PrFEQ. These models have been among the most widely used and generally recognized, mainly by the number of studies reported in the literature that addressed them (TROLLE et al., 2012; COLLÉTER et al., 2015).

Mathematical models applied to lakes and reservoirs

Since the development of the first mathematical models applied to aquatic ecosystems, the main objective was to model some components of the aquatic environment, i.e., a hydrological parameter, such as currents or thermal stratification, a parameter of water quality, such as concentrations of nutrients, or even some key communities, such as primary producers. Experiments with global models have shown that the coupling of hydrodynamic, ecological, and water quality modules produced valid results, and is recommended for a better understanding and representation of the functioning of lakes or reservoirs (ELLIOTT et al., 2007). Lentic environments with great heterogeneity should be represented by three-dimensional models with a high number of modules and parameters (LINDIM et al., 2011).

Eutrophication modelling

A remarkable advance of mathematical models applied in aquatic ecosystems was their use in the simulation and prediction of eutrophication of lakes and reservoirs. Eutrophication models may consider variables of water quality, hydrodynamics, and ecological relations (ZHANG et al., 2008), and may include climatological information. In the study conducted by MAO et al. (2008), results indicated that the dynamics of eutrophication in lakes could suffer great influence from the action of the winds and sediment transport, which should be considered key elements. Water temperature is another parameter with a simulated effect on the dynamics of reservoirs, especially with respect to nitrogen, phosphorus, and chlorophyll levels, and may influence the eutrophication of the systems (XU et al., 2012). It is worth noting that adding new modules and modelling elements can bring benefits to the accuracy and efficiency of global models.

In reservoirs, computational representation of ecosystems can be a decisive tool for their management and operation. PARK et al. (2014) created a model to understand how changes in the outflow from reservoirs could affect the entire dynamics of water bodies. With the use of this model, it was possible to estimate an ideal water flow rate to avoid the increase in the levels of phosphorus, nitrogen, and chlorophyll in reservoirs and; consequently, their eutrophication. YAJIMA & CHOI (2013) created a model to assess the effects of the construction of a channel for water abstraction in the upstream of a reservoir. This modelling showed that the structural alteration affected the inputs of nutrients to the reservoir, the concentrations of nutrients and chlorophyll, and also caused changes in the energetic and thermal balance of the ecosystem.

In order to understand primary production and producer communities, some studies have assessed the life and development phases of cyanobacteria through computational modelling (HENSE & BECKMANN, 2006). These algae cause problems in the use of water resources around the world, and this type of mathematical model helps us understand the behaviour of populations and predict blooms. A mathematical model for predicting harmful algal blooms was created for lakes and reservoirs (LI et al., 2015). This model identified which biotic and abiotic parameters were most important for the occurrence of blooms of blue and green algae, with a selection of 10 variables out of 48 initially analysed. It is worth noting that global eutrophication models are considerably versatile and provided relevant answers for the management of water and ecological quality in aquatic environments.

Ecosystem modelling

Ecopath with Ecosim (EwE) (CHRISTENSEN et al., 2005) is one of the most used models to estimate properties of ecosystems and energy flows in aquatic environments. The main objective of most models is to improve the management of ecosystems and fishery resources (STÄBLER et al., 2016). It is possible to simulate different anthropic disturbances, such as changes in fishing effort (RAKSHIT et al., 2017), banning of illegal fishing (BACALSO et al., 2016), and the biological invasion process (KUMAR et al., 2016). In this way, ecological modelling can be used to understand several environmental conditions, allowing the prediction of the future state of aquatic ecosystems submitted to some environmental/anthropic stress. This predictive capacity is particularly important in tropical continental environments, which are naturally vulnerable ecosystems with a high risk of environmental degradation (GUO et al., 2018).

Anthropogenic stresses notoriously affect these aquatic ecosystems. Approaches that allow a wide assessment of impacts are increasingly needed to prevent the potential loss of ecological services of these environments. A food web describes the pathways that energy and nutrients travel within the ecosystem, ranging from resources such as organic matter (detritus) to species that spend only part of the time in that environment, such as migratory fish or waterfowls (THOMPSON et al., 2012). All species within an ecosystem can be classified into trophic levels, from level 1 (primary producers), with the other components receiving increasing numbers according to their diets. Therefore, the species of upper trophic levels predate those of lower levels. Understanding these energy flows enables estimating ecosystem indicators. An environment can be modelled using EwE to calculate mass balance within the system (Ecopath module), estimate energy flows and systemic properties, and even dynamically simulate the biomasses of the populations over time (Ecosim module). This model has been used in the last four decades mainly to assist in the management of aquatic ecosystems (VILLASANTE et al., 2016).

Modelling of aquatic ecosystems submitted to aquaculture activities

Among the possible uses of reservoirs, the rapid development of aquaculture activities in net-tanks has been one of the main problems. However, among the main anthropic impacts assessed, the effects of aquaculture activities are among the least studied, especially in tropical environments, as can be observed in the survey performed for EwE (COLLÉTER et al., 2015). One of the major challenges today is to measure how much an aquatic ecosystem can support in terms of cultivated organisms, aiming to maintain the environmental, social, and economic sustainability of aquaculture activities (MOURA et al., 2016). Regarding this issue, mathematical modelling has been successfully used in order to determine the support capacity of systems with respect to cultivated species. It is important to consider that support capacity is an attribute of ecosystems; therefore, approaches that model their operation in a global way can provide important answers about the effects of aquaculture on aquatic environments.

One the most widespread modelling approaches in aquaculture is the use of nutrient mass-balance models, especially phosphorus (DILLON & RIGLER, 1974; VOLLENWEIDER, 1975). These models are simple and based on information about phosphorus content in cultivated organisms and in their diets, and about some hydrological parameters, such as water renewal time and phosphorus retention coefficient of the reservoirs. CANZI et al. (2017) modelled the best areas for fish production in net-tanks in the Itaipu reservoir, state of Paraná, Brazil, by means of phosphorus mass balance, making the selection of the most appropriate regions according to the local capacity of phosphorus assimilation generated by fish farming. The authors estimated the support capacity of each place, and, finally, the maximum capacity that could be produced in the whole reservoir. Using the same approach, support capacities for net-tank fish farming have been calculated in several environments (MHLANGA et al., 2013, FEIDEN et al., 2015, GUNKEL et al., 2015). Results of this type of model are strongly dependent on the estimation of phosphorus emission by the cultivated animals, which may be important information for the model than for parameters, such as water volume of lakes or reservoirs. Other approaches included the hydrodynamic modelling of waste dispersion generated by net-tanks, and modelling of processes, such as sedimentation and phosphorus assimilation by primary producers. In this way, it is possible to simulate a maximum level of aquaculture production with a lower risk of eutrophication of aquatic environments (LIN et al., 2016).

Bivalve cultivations and their trophic interactions with the aquatic ecosystem were modelled using the EwE by BYRON et al. (2011a, 2011b), with the main objective of determining support capacities. Using trophic models —such as EwE— for this purpose is a breakthrough, because traditional models of support capacity for aquatic environments neglect important aspects of trophic ecology. The support capacity was considered to be equal to the maximum density of bivalves that would not cause imbalance in native populations. It was estimated that the biomass of cultivated bivalves could be increased up to more than 600 times, and that values above this limit would cause the collapse of the phytoplankton population.

In another case, the modelling of a bivalve culture system in the estuarine region identified that, according to the maturity indexes estimated by the model, the biomass produced would exceed more than twice the support capacity, even though the high maturity of the ecosystem suggested a high resilience (OUTEIRO et al., 2018). Diverse bivalve cultivations in different environments have already been modelled in order to determine the capacity of ecological support using the ecosystem approach of the EwE model, which considers the equilibrium of local aquatic populations (KLUGER et al., 2016; HAN et al., 2017). We observed the ability of ecosystem modelling to produce holistic responses, estimating characteristics for various aspects of ecosystem functioning, and the effects caused by aquaculture activities.

The understanding of the relationships between environmental conditions and aquaculture systems is of fundamental importance in the local and global planning of management actions. Mathematical models can be used to assess the vulnerability of aquaculture activities to climate change, helping identify regions and methods of cultivation with higher levels of risk that require priority management actions (FAO, 2018). Currently, one of the main aquaculture systems is fish farming in net-tanks. This system suffers a strong influence from environmental and climatic conditions of the place where it is installed, and, at the same time, exerts pressure on the environment through the waste stream. The impact caused by this type of system installed in lakes or reservoirs on the aquatic ecosystem mainly depends on: (i) Use of nutrients in the form of feed; (ii) Generation of effluents; and (iii) Environmental nutrient cycling (ALTIERI, 2002).

As one of the main problems of aquaculture is the generation of waste, the bioenergetic models were developed to assist in this estimation and have exhibited high accuracy. These models take into account environmental conditions such as temperature, species characteristics such as basal metabolism, and feed properties such as digestibility (BUENO et al., 2017). One of the prominent bioenergetic models in aquaculture has been implemented in the FishPrFEQ software (CHO & BUREAU, 1998), which incorporates growth equations for fish at different stages of cultivation. BUENO et al. (2017) created a bioenergetic model to simulate the production of tilapias in net-tanks, which allowed daily estimates of phosphorus emissions from the cultivation system throughout the productive period and in all breeding phases.

These models can be particularly accurate, because they aggregate historical information of previous productive cycles, which improves the predictive capacity of the simulations. Thus, they can be used to determine the ideal amount of feed to be offered to the animals on a daily basis (CHOWDHURY et al., 2013). Therefore, it is possible to optimise the productive process from the responses in several aspects, such as feed wastage and amount of feed used, improving feed conversion and assisting in planning the waste treatment process (CANALE et al., 2016).

The models can also be applied in order to simulate the action of measures for water resources management, thus predicting their effects on the ecosystem as a whole and helping in decision making. Several scenarios with different tilapia biomasses in extensive polycultures were modelled with EwE by XU et al. (2011) in order to determine the maximum biomass produced that would not affect the mangrove area in which the system had been installed. The results showed that increases in the density of cultivated tilapia would have a direct effect on the zooplankton community and on the detritus of the system. In addition, indirect effects would be transferred by the food web, altering the biomasses of the populations of upper and lower trophic levels. This way, the understanding of the direct and indirect effects of aquaculture allows determining a level of production in line with the protection of aquatic communities and ecosystems, thus helping promote directives on the expansion of activities and management of natural environments.

CONCLUSION

Efforts to develop increasingly comprehensive mathematical models that encompass much of the complexity of aquatic ecosystems pose a challenge to current ecological modelling. The trend becomes clear when we observe the increased number of ecosystem models created in recent years. These models encompass aspects of the food web, hydrodynamics, biogeochemical cycles, water quality, meteorology, and ecological processes.

The role of ecological and food web modelling in the understanding of aquatic bodies and the possible impacts caused by aquaculture activities becomes evident. These tools can help observe the interactions between cultivation systems, physical environments, aquatic communities, and other anthropogenic activities, such as fishing. It is important to highlight that the possibility of simulating scenarios and predicting events and processes —such as eutrophication— makes modelling a great ally of water resource management.

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DECLARATION OF CONFLICTING INTERESTS

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

AUTHORS' CONTRIBUTIONS

All authors contributed equally for the conception and writing of the manuscript. All authors critically revised the manuscript and approved the final version.

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