THESIS OF THE PhD DISSERTATION

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GÖDÖLLŐ

2024

HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES

PROCESS MODEL-BASED ASSESSMENT OF ENVIRONMENTAL IMPACTS AND ECOSYSTEM SERVICES OF FISHPOND AQUACULTURE

DOI: 10.54598/005880

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1. INTRODUCTION AND OBJECTIVES

1.1 Introduction

The freshwater fishpond sector is an important component of European aquaculture, with Central and Eastern European countries accounting for about 38% of European freshwater aquaculture production (Gyalog et al. 2022). Fishpond systems in these regions are mainly managed using extensive or semi-intensive methods with relatively low yields. These fishponds operate as interconnected ecological units where technological and natural processes coexist and provide a range of ecosystem services (ES) such as provisioning, regulating and cultural services.

The interactive nature of pond aquaculture with the surrounding environment, including adjacent reed and marsh vegetation, requires consideration of various internal and external factors that affect production and other ESs. Effective management of these systems requires an understanding of how different pond management practices affect the complex dynamics of fishpond ecosystems. Difficulties in identifying and quantifying multi-dimensional environmental impacts make it difficult to integrate them into decision-making processes and thus create obstacles to successful policy and regulatory development.

In this context, a model-based assessment of the environmental impacts and ES of fishponds could prove very informative in suggesting strategies to increase their productivity, efficiency and quality while reducing operating costs. Numerous modelling tools and techniques exist for the fishpond itself, but their application is limited by their data-intensive features, lack of sophisticated biophysical linkages, few options for customization or application to a wide range of scenario analyses. More generalizable, reproducible models based on conservation law-based dynamic processes are needed to understand the systemic environmental interactions of the complex processes responsible for generating ES in the fishpond system.

1.2 Objectives

The main aim of this work was to further develop, implement and test a novel process model-based solution for the quantitative analysis of environmental impacts and ecosystem services in fishpond aquaculture, including a managed pond food web and reed vegetation.

Following this general aim, the specific objectives of this study are as follows:

1. To improve the previously developed and validated Programmable Process Structure (PPS) - based biophysical fishpond model and enhance aspects of model reusability for application to a wider range of differently managed fishponds.
2. To adapt the PPS-based simplified plant model (Varga 2022) and implement existing biophysical knowledge and data for emergent macrophyte vegetation to develop the reed-related model component for the fishpond-reed agroecosystem.
3. To construct a process-based model of the coupled agroecosystem including the managed pond food web associated with macrophyte/reed-like vegetation areas. This includes building a PPS-based simulation model from unified reusable elements to account for physical, chemical, biological, ecological, and management sub-processes.
4. To analyze the modelled dynamic balances and causal relationships behind the environmental interactions and to evaluate the impact of different hypothetical fishpond management scenarios on the environmental interactions.
5. To showcase the assessment of ecosystem services (ES) and dis-services (EDS) indicators of pond aquaculture using the simulations of environmental interactions.

2. MATERIAL AND METHODS

The first part of this work focused on the improvement of the reusability aspect of a previously published reference biophysical fishpond model (Varga et al., 2020) to incorporate the characteristics of a wider range of differently managed fishponds. A reference model was subjected to a stepwise improvement using measured data, progressing from simpler ("reduced") cases utilizing the natural food web to more complex ("extended") cases with feeding, manuring and inorganic-fertilizer input.

The reference model considered was built as a component of the ClimeFish project's Decision Support System (DSS) for assessing the effects of climate change in fishpond aquaculture. Although the reference model provided robust simulations, it had some model-related limitations. For example, the model was only partially validated, as experimental data for initial values of various food web components could only be obtained from the literature. Certain additional factors, such as the high fertilization rate or input of inorganic fertilizer - its dry matter, nitrogen and phosphorus content were also not considered. As the detritus levels in this pond model were restricted to a narrow range due to the low fertilization rate, the reference model could not account for the large sedimentation and resuspension events. Other data-related limitations included the lack of site-specific solar radiation and humidity data sets, so only estimated values from other Hungarian data sets were used.

A stepwise approach was used to develop, refine, and validate the reference model. For this improvement, data were collected from the pilot experiments conducted in two ponds (i.e., CS6, CS7) in 2021 and three ponds (i.e., CS2, CS3, CS6) in 2022 at HAKI AKI MATE (Szarvas). These ponds were sampled for chlorophyll-a, dissolved oxygen, temperature, zooplankton, feed, and fertilizer inputs, stocked and harvested fish. Site-specific meteorological data were also collected. The reference model was used to develop a computational model for pilot case studies, termed a “reduced model” (2021CS6) describing extensive fish production with low stocking rates and no external nutrient supply, and an “extended model” (2022CS6 and 2022CS2) describing intensive fish production with higher nutrient supply, with manure and optional inorganic fertilizer. A third case was also developed for food web extension, where model functionalities were further extended to consider groups of cyanobacteria and eukaryotes instead of a single state variable of phytoplankton by creating a “hypothetical extended scenario”. A continuous, iterative process was carried out to improve the parameters and specifics of the model. Finally, the refined model underwent several rounds of testing, improvement and validation calculations using data from two further pilot instances (2021CS7 and 2022CS3).

For additional validation of the improved model and to account for sampling and measurement errors, we used data from an additional set of experiments conducted during the ARRAINA (Advanced Research Initiatives for Nutrition and Aquaculture) project in 2014 at MATE AKI HAKI, Szarvas. Parallel experiments were conducted in Three pair of pond (2+2+2) to test alternative diet types (plant, fish oil and vegetable oil based). Finally, the improved fishpond model was tested for scale-up to a large production pond with very limited data from the site. Data on pond area, stocked and harvested fish biomass, feed and manure from a fish farm site in Biharugra (Hungary) were used for this up-scaling process. The meteorological conditions and some other missing data were adapted from the pilot experiments. All other model parameters and program prototypes remained consistent with the previously validated model.

Fishpond processes are highly interactive with the surrounding environment, particularly the adjacent reed vegetation. To account for the wide range of environmental interactions associated with fishpond agroecosystem, a model is required that can consider the holistic processes and functions associated with the pond food web and reed vegetation. Inspired by a real fishpond ecosystem, the above improved fishpond model was extended to include the subsystems of reed vegetation (mainly monospecific strands of *Phragmites australis*) inside and on the terrestrial part of the ponds.

To construct the individual reed model, a medium complexity stoichiometric plant growth model developed by Varga, 2022 was modified based on specific knowledge of Phragmites australis growth characteristics and phenology from literature sources and other modelling studies such as Asaeda & Karunaratne, 2000. Based on information from literature and previous modelling studies. The total biomass of the individual reed plant was divided into above-ground organs (stems, leaves and products - here referred to as panicles) and below-ground organs (rhizomes and roots). In addition, specific information on the different phenological phases, the proportion of each plant part in each growth phase, the respiration rate of each plant part and the density of shoots were incorporated into the plant model. Differences in phenological characteristics and other parameters from published literature references were also noted and were further refined through model calibration.

In the present modelling approach, stoichiometric principles have been used, to consider conservation measures in dynamic modelling. With a focus on C, H, O, N and P atoms, the state-representing elements in the fishpond model (e.g., food web elements, feed, fertilizer, inflow water, pond water), in the reed plant model (i.e., for each plant part - leaves, stems, roots, rhizomes and panicles) and in the other environmental components (e.g., soil layers and atmosphere) were extended with respective stoichiometric compositions. The reed model accounts for stoichiometric variation both within and between phenological periods. For pond food web elements, the differences in stoichiometric composition between the stoichiometric input of predators and prey were calculated. Excretion incorporated this difference in the detritus, which had a dynamic stoichiometric profile. In addition, moisture content was also considered for each plant part of the pond food web, as it plays an important role in the overall push and pull logistics in plants and material flows between different compartments (both vertically and horizontally).

As a general framework, the newly consolidated experimental version of the PPS (Varga et al., 2022; Varga & Csukas, 2024) has been used for the automated generation and execution of the underlying unified process models. PPS models consider non-linear causal interactions of characteristic physical, chemical, biological, ecological, and technological processes, governed by conservation laws. The Programmable Process Structures (PPS) framework has been used to automatically generate these complex biophysical models. PPS supports this by generating predictive coupled process models that adhere to first principles and account for non-linear causal interactions across physical, chemical, biological, ecological, and technological systems. PPS provides unified solutions for the implementation and coupled execution of different unified sub-models by generating them from common state and transition meta-prototypes. The generation of process models is based on a simple ontology of a special state-transition network of the underlying processes. Most variables are local, which facilitates code reuse and simplifies variable naming in local applications.

Deviation between measured and simulated values for both the improved fishpond model and the coupled pond food web - reed model, was calculated using the normalized root mean square error (NRMSE, %). The first set of pilot experiments conducted in 2021 and 2022 did not include parallel experiments, so measurement and sampling errors were not available, making it difficult to identify the true model-related errors. Therefore, the data from parallel experiments (2-2-2, with 3 differetn types of feed) collected in 2014 were used to calculate the standard deviation (SD) to show the differences in the parallel measurements. Next, the RMSE values were calculated for the measured and calculated data, and the differences were explained by comparing the respective SDs. In the case of the reed plant model, in the absence of actual field measurements, this model was approximately validated using data from empirical studies in the literature.

3. RESULTS AND DISCUSSION

3.1 Refined fishpond model

The improvement of the fishpond model led to a deeper understanding of pond food web components model components and their links with environmental and managerial factors. The Fig. 1 represent the different components of the refined fishpond model and their associations.

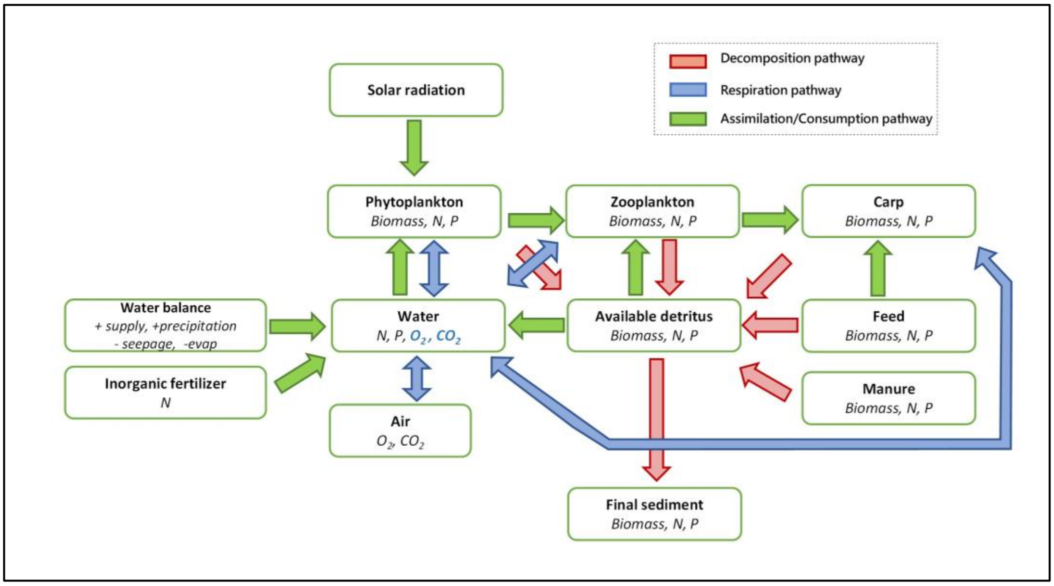

Figure 1. Investigated fishpond model components

To generate the model for **first reduced case (2021CS6),** additional state elements such as feed, fertilizer and the associated transition elements were switched off in the program code. Regarding the data used, it was observed that the initial conditions of phytoplankton, zooplankton, detritus, and their N and P concentrations recorded during the early season experiments were variable and, in some cases, inaccurate. In natural pond food webs without external feeding, initial levels of phytoplankton, zooplankton, and detritus strongly influence the system through to positive feedback loops. For this reason, these initial values were fine-tuned during the systematic simulations. At this stage, the model did not follow the rapid increase in chlorophyll-a at the end of the production season (Figure 2 (a)). This led to the idea of extending the food web in the model, based on the hypothesis of a temperature-driven emergence of cyanobacteria, in later stages of model development.

The model simulations based on the **second pilot experiment (2021CS6)**, where organic manuring was significantly higher than in the reference model, show a sudden increase in detritus after manuring, which then gradually sediments Fig. 2 (b). Therefore, a new prototype program was developed in the improved model to consider the permanent sedimentation of a certain fraction of detritus together with the associated amount of N and P. The sedimentation rate was directly related to the amount of detritus and increased proportionally with it.

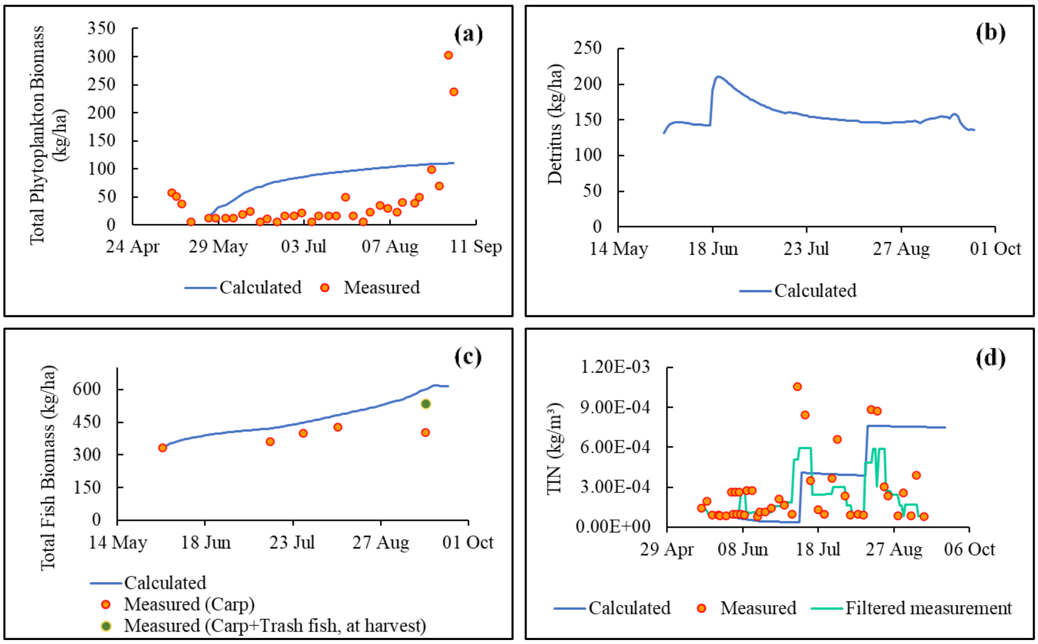

Figure 2. Simulated biomass of **(a)** phytoplankton in the case of experimental pond 2021CS6 and **(b)** detritus and **(c)** fish; **(d)** total inorganic nitrogen (TIN) concentration in the case of experimental case 2022CS2

During the cyclic improvements, the parameters "Sed" i.e., the sedimentation rate coefficient (1/day) and "D_{min}" i.e., the lower limit concentration of available (suspended) detritus (kg/ha) were calculated to be 0.6 1/day and 132 kg/ha, respectively. Moreover, in view of the actual composition of the manure, the prototype of the program for manure decomposition was also improved.

Fig. 2 (c) shows the simulations for the fish biomass produced system under the actual conditions (e.g., available zooplankton, oxygen, etc.), so it calculates slightly higher value. Supplementary information from the experiment site revealed that in addition to carp, the total measured fish biomass also included a substantial amount of trash fish (134 kg). Therefore, while comparing the model simulations with the measured data, appropriate summarized value of measured carp and trash fish were used.

In the case of the **third pilot experiment 2022CS6**, appropriate model components were added to take account of the additional input of inorganic fertilizer. The resulting model simulations show that the ammonium nitrate in the inorganic fertilizer dissolves immediately (Fig. 2 (d)) and its nitrogen content appears in the water. This is different in the case of nitrogen and phosphorus from the organic manure, as these can be trapped in the sediment as described above.

Previous improvements in terms of structure and parameters were kept fixed in the next steps. The **first validation experiment (2021CS7)** included the case of quadrupling the manuring pattern (i.e., 3 + 2 + 3 + 3 t/ha manure). The corresponding model simulations showed that although the input of organic manure was quadrupled, only a small increase in the total biomass of produced fish was observed. The outputs of the model using data from the case of the **second validation experiment (2022CS3)** showed a peak in the measured value of dissolved oxygen in the middle of the season Fig. 3(a). This phenomenon can be attributed to temporary activation of the paddlewheel aerators during warm days. Thus, the simulation results deviate from the measured values in this case as the model could not account for the aerator activity.

Based on the previously described differences between the measured and simulated values of the phytoplankton concentrations, particularly the high values at the end of the season, an attempt was made to investigate this phenomenon based on a **hypothetic case** developed in line with the explanations from literature (Jeppesen et al. 2011, Potužák et al. 2007). Cyanobacteria has higher optimum growth temperatures, so their concentration increases with warmer temperatures, which in turn reduces the appetite of zooplankton, resulting in a peak in chlorophyll-a at the end of the production season Fig. 3 (b). Based on this hypothesis, two subgroups of cyanobacteria and eukaryotes were distinguished within the phytoplankton category and the program code was modified accordingly.

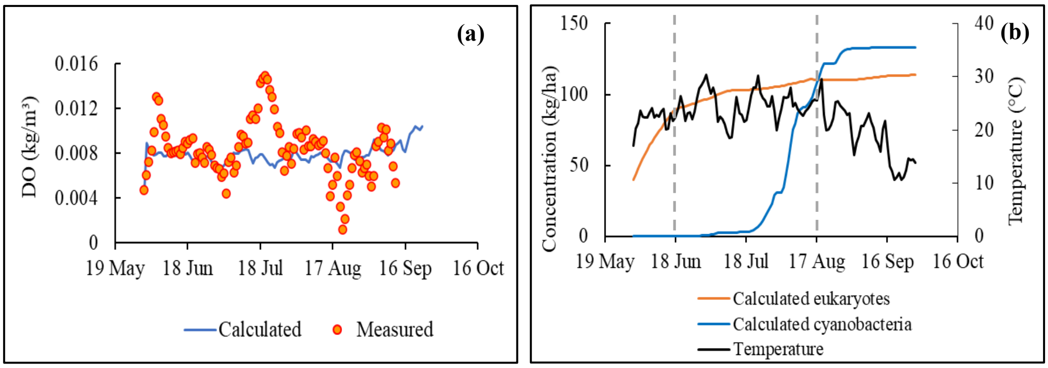

Figure 3. (a) Dissolved oxygen content in water in the experimental case 2022CS3 used for validation, **(b)** Total concentration of eukaryotes and cyanobacteria in the hypothetic case based on pilot pond 2022CS3

Regarding validation, the NRMSE values ranged from 1.5% to 58.4%, i.e., the model tended to either over- or underestimate certain components. In this case, the NRMSE values included sampling, measurement, and model errors. Thus, the model holds further scope of improvement considering the additional measurements for validation with details on sampling and measurement errors. On the other hand, the RMSE and SD values calculated for the additional set of experimental data from 2014 show that where there are higher values of model error, the experiments are also characterized by a greater range.

Finally, the improved pond model was used for up-scaling by using the available limited amount of data on pond area, stocked and harvested fish biomass, and feed and manure from a fish farm site in Biharugra (Hungary) for the years 2014 to 2016. As a first trial, the fish biomass was simulated in this case. Although the model is also capable of simulating other sort of environmental impacts.

3.2 Coupled fishpond and reed model

A simplified conceptual model for the fishpond-reed agroecosystem, as presented in Fig. 4 was constructed to visualize different compartments and their connections

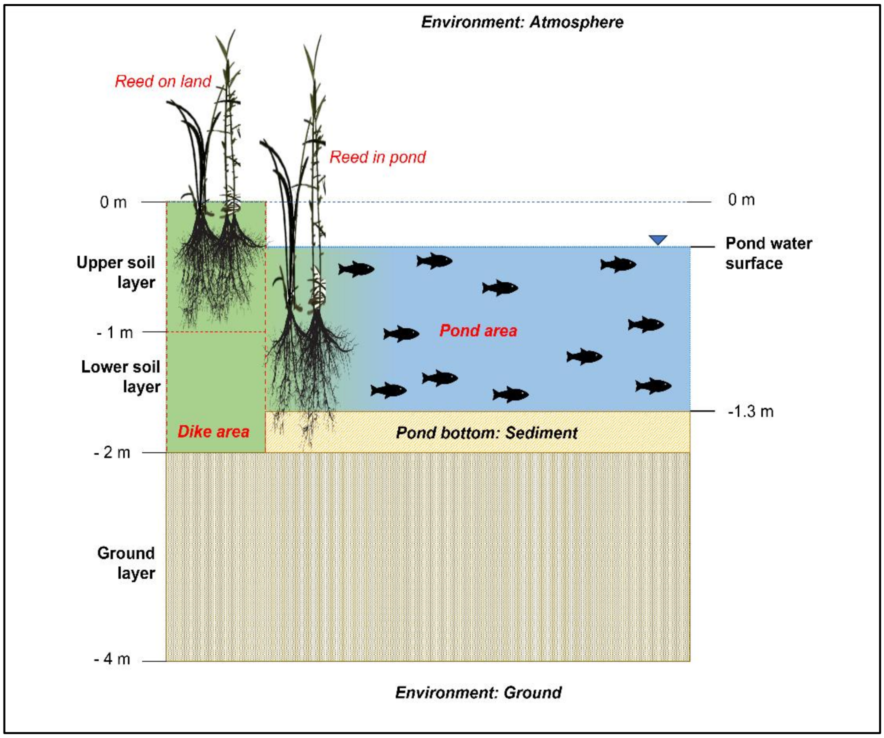

Figure 4. Conceptual model of the fishpond-reed coupled model

The main compartments considered in the model are: [pond] containing fish, food-web, and reed vegetation; [land_reed] consisting of land with reeds around the pond; [groundlayer] - the soil beneath the pond and land; [atmosphere] representing the air and meteorological conditions; and [env] for input and output material storage outside the model's scope. The horizontal movement of the water and nutrient is based on the hydraulic and nutrient gradient.

For the reed related component, a refined plant growth model of *Phragmites australis* model was constructed. And in next steps, data from various literature sources (Asaeda & Karunaratne 2000; Soetaert et al. 2004 and Karunaratne & Asaeda 2000) was used for its approximate validation. The plant model simulations for growth of different plant parts were closer to the data points used from a case study from Czech Republic with low NRMSE values (i.e., between 6% and 34% for the different plant parts).

In the coupled model structure pond food web and reed, the actual state elements in these compartments represent the corresponding sets of extensive quantities and input signals as well as the calculated intensive quantities (concentrations) and output signals (e.g., state_species, state_materials, state_meteo, state_envoutstorage etc). The actual transition elements inside or between these compartments represents the modelled transport and transformation processes, as well as rules (e.g., trans_evapotranspiration, trans_t_carp, trans_material_decomp, trans_water_balance etc).

During the research, the sensitivity of the pond model to the initial conditions of food web elements (especially zooplankton) was also recognized. After analysis, two significant and overlapping phenomena were identified. These includes the problems of initial conditions in seasonal modelling with hardly measurable initial values, resulting in sensitive, infeasible model starts; and the interaction of initial conditions with positive feedback loops in the food web. Having identified and analyzed these phenomena, we introduced solutions in two steps to deal with these problems in the model. The first step was to introduce an improved sedimentation model (as described in the case of pilot pond experiment 2022CS6). However, this was not sufficient, so in the second step, in accordance with the requirements of the combined pond-reed model, the concept of a “hibernated” (or “passive”) initial state was introduced, and seasonal calculation was replaced for the whole year, as well as multi-year simulation. After incorporating these improvements, the coupled fishpond-reed model became robust to the initial state of the pond at the start of the model. This factor clearly demonstrates the applicability and generalizability of the model to different fishpond scenarios. Stakeholders relying on the model for decision making can be assured of the extent to which the model outputs can be trusted, especially when the initial conditions are not well defined and subject to variation.

In order to test and refine the coupled fishpond and reed model, a baseline case was set up based on a typical Hungarian fishpond (10 ha, 1.3 m water depth). The model starts on 1 February with a 10-day pond filling to 130,000 m^3. Water is released for 20 days after harvest until the water level reaches 0.1 m. The stocking density is 300 kg/ha and the fish production season is from 1 April to 31 October. Feeding rules depend on the weight of the cap and 3 t/ha of cattle manure was assumed to be added on 3 February, followed by 2 t/ha on 1 June, 1 July, and 1 August (i.e., in total 9 t/ha during the entire production season). While interpreting the results it must be noted that this manure input was hypothesized based on the previously described pilot pond experiment 2022CS3 and is relatively high as compared to the usual pond management practices. Terrestrial reed covers half of the perimeter and pond reed covers 20% of the surface, with 75% of the above-ground reed cut annually. Five-year long simulations were run continuously, even between production seasons, to represent certain parts of the food web and nutrients that remain after the pond water has been discharged. It also showed the stability of the model by reaching a trend over time. Some examples of the quantitative outputs from the model are shown in Fig. 5 (a) to (d).

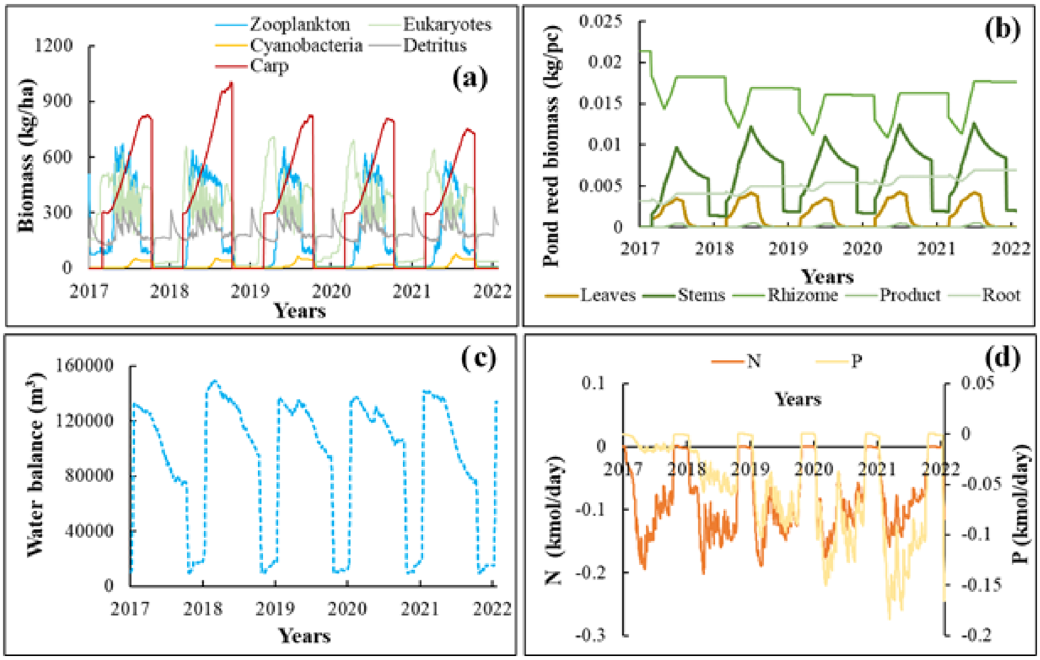

Figure 5. Simulations for **(a)** biomass of fishpond food web elements, **(b)** biomass of different plant parts of reed growing inside the pond, **(c)** water balance and **(d)** nitrogen (N) and phosphorus (P) lateral flows in the upper soil layer (from the pond to the reed compartment)

Next, based on the baseline scenario, twenty-one hypothetic scenarios were created for fishpond-reed ecosystem in order to investigate the change in the input and output environmental interactions. These scenarios can be summarized as follows: *Scenarios 1-4*: Fishponds with pond reed varying from 1% to 30%, no reed management; *Scenarios 5-7*: 75% of pond reed cut and left in the area; Scenarios 8-10: 75% of pond reed cut and harvested; *Scenario 9*: the baseline case; *Scenarios 11-12*: Terrestrial reed density at 0.5 times (35 plants/m²) and 1.5 times (105 plants/m²) the baseline and unchanged area; Scenarios 13-15: Terrestrial reed with varying densities (35, 70, 105 plants/m²), cut and removed; *Scenarios 16-18*: Baseline with low (200 kg/ha), medium (400 kg/ha), and high (600 kg/ha) stocking densities and *Scenarios 19-21:* Baseline with no fertilizer, double fertilizer and one-third fertilizer input (ID 21 more closer to the usual pond practices).

The results of the model simulations of the scenario represent the changes in input and output flows and are represented by the annual average of five years of simulations of different nutrients such as N, P, O_2, CO_2 and water. The results indicate that most nutrients are introduced into the system through the water supplied to fill the ponds. Therefore, when assessing the environmental impact of an agroecosystem, it is important to identify the source and quality of the input water used and the options for reusing the discharged water.

For Scenarios 1 to 4, a direct effect of the increase in reed cover can be seen in the reduction of nitrogen and phosphorus in the effluent and bio-waste. It can be seen from the simulations in Fig. 6 (a), the increasing percentage of reed cover in the pond does not necessarily interpret that more carbon dioxide being stored in the system (e.g., when reed cover inside the pond reaches 30%) because the CO_2 budget is also affected by released CO_2 as output during respiration.

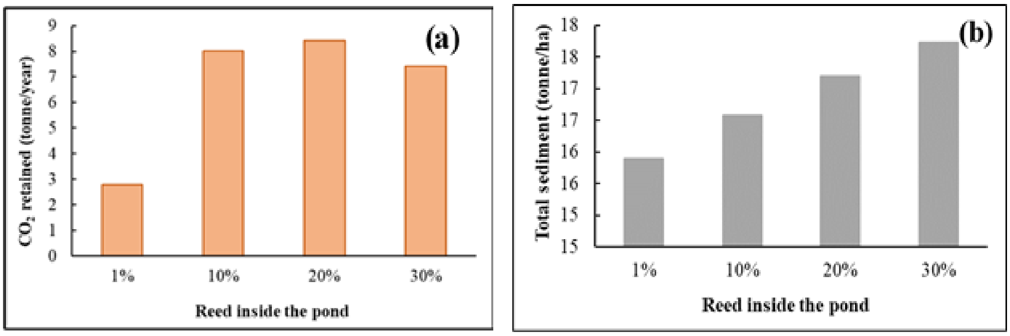

Figure 6. **(a)** Total amount of carbon dioxide retained in the fishpond-reed system (kg/year), **(b)** Total sediment in the pond (tonne/ha) in the case of Scenario ID 1 to 4

High vegetation cover results in more littering, which decomposes into sediment (as shown in Fig. 6 (b)), which further accumulates in the pond and have negative effects on fish production activities. Thus, dredging and utilizing the pond sediment regularly can be a viable solution.

Fig. 7 (a) and (b) illustrates the effects that are caused by the removal of the cut reed from the pond. If the cut reed is taken out of from the system, then the total amount of sediment slightly decreases. The harvested reed biomass also serves as additional utilizable material such as for bio-based energy, roofing material, fodder for cattle etc.

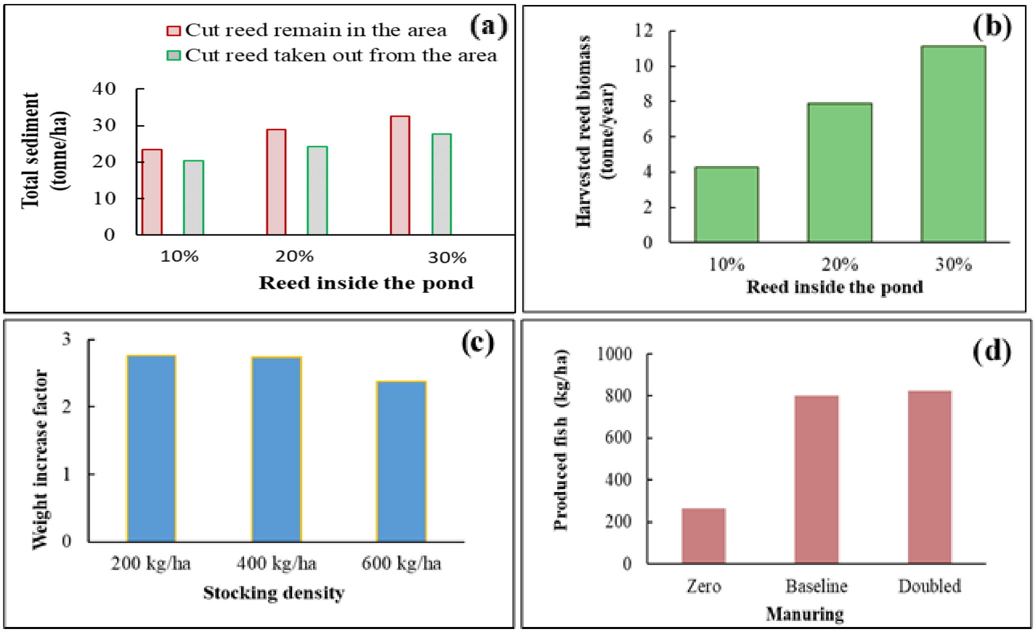

Figure 7. Model simulations for **(a)** effect of reed management (Scenario ID 5, 6 & 7 and 8, 9 & 10) on the amount of total sediment in the pond at the end of one production season and **(b)** biomass of harvested reed, **(c)**weight gain factor of fish per fish (Scenario ID 16, 17 & 18) and **(d)** Produced fish per year (Scenario ID 9, 19 & 20)

Fig. 7 (c) shows that as stocking density increases (with limited manure and feed input), the oxygen consumption of the fish also increases, which can bring the DO content of the pond below the threshold, further reducing the weight gain factor or ratio of the fish. Furthermore, an excessive increase in manure input (9 t/ha - 18 t/ha) correlates with an increase in sediment mass in the pond This can be seen in Fig. 7 (d), where there is not too much difference in the fish biomass on doubling the manure input. In the case of no manuring, it is evident that the fish production is low. Therefore, the constructed model has the potential to be applied to different scenarios and to provide interesting insights into the environmental interactions between the fishpond and the surrounding environment.

3.3 Model outputs and ecosystem services assessment

The model simulations for different environmental interactions were used to determine the positive impacts (ecosystem services (ES) and negative impacts (ecosystem dis-services (EDS)) from fishpond aquaculture. First, ES indicators were selected from the extensive list of indicators provided by Maes et al. (2014) and specific pond aquaculture research (Hoess and Geist, 2022; Rey-Valette et al. 2024). Next, following the Common International Classification of Ecosystem Services (CICES) (Haines-Young & Potschin-Young, 2018), the selected indicators were modified and divided into three main categories: provisioning services, regulating, and maintaining services, and cultural services. Table 1. shows the categorization of fishpond aquaculture ES, highlighting their grouping, class, division and measurable indicator, and their relationship to the appropriate model compartment, element and process was also identified.

Table 1. Classification of model outputs as ecosystem services

Division	Group	Class	Indicator	Model compartment	Model element/ process	Explanation
			Provisioning services			
Material and Energy	Biomass and Biomass-based energy sources	Materials from plants and plant-based resources	Harvest-ed reed biomass for various purposes	Environ-ment	Product reed	Harvested photo-synthetic reed biomass
Nutrition	Biomass	Animals from in-situ aquaculture	Aquaculture production	Pond	Produced carp	Harvested carp at the end of the production season
Non-aqueous natural abiotic ecosystem outputs	Mineral substances used for nutrition, materials, or energy	Mineral substances used for material purposes	Nutrient rich sediment from the pond	Pond	Sediment mass	Potential utilization of pond sediment for growing different vegetables crops etc.

Table 1. Continued

Division	Group	Class	Indicator	Model compart -ment	Model element/ process	Explanation
Regulatory and maintenance services						
Maintenance of physical, chemical, and biological conditions	Atm. Compos-tion and climate regula-tion	Global climate regulation by reduction of GHG conc.	Carbon sequestra-tion Carbon storage	Land reed + Pond reed	Photo-synthesis	CO_2 input from air
Regulation of physical, chemical, biological conditions		Regulation of temperature and humidity, including ventila-tion and transpiration	Local moisture recycling capacity	Land reed	Evaporation	Movement of water from soil to air
				Land reed + Pond reed	Evapo-transpiration	Emission of water vapor from plant surface
				Pond	Evaporation	Movement of water from pond to air
Other types of regulation and maintenance service by living processes	Other	Other	Micro-scale oxygen production	Land reed + Pond reed	Photo-synthesis	O_2 released to the air
			Aquatic oxygen production	Pond	Food web primary production	O_2 produced by eukaryotes and cyanobacteria, which is used by fish.
				Land reed	Side flow	Accumulation in the soil through lateral flows
					Uptake by plant	Uptake from upper soil solution by reed plant

Table 1. Continued

Division	Group	Class	Indicator	Model compart-ment	Model element/ process	Explanation
			Regulatory and maintenance services			
Mediation of flows	Liquid flows	Hydro-logical cycle and water flow maintenance	Seepage of water	Ground layer	Seepage	Downward movement of water pond to ground layer
			Soil moisture	Land reed	Side flows	Moisture retention in the soil around the pond
			Water store capacity	Environ-ment	Water store	Water collected in the pond
Mediation of waste, toxics, and other nuisances	Media-tion by eco-systems	Filtration/ sequestration / storage/ accumula-tion by ecosystems	Nitrogen and Phos-phorus retention and removal	Ground layer	Seep-age	Movement from pond into the soil
				Pond	Detritus	Accumulation in sediment
				Land reed	Side flow	Accumulation in the soil through lateral flows
					Uptake by plant	Uptake from upper soil solution by reed plant

The next steps involved using quantitative model simulations to generate a rule-based qualitative layer, and identifying proxy indicators to assess other ES such as cultural services and habitat maintenance. For example, water clarity which is closely linked to the aesthetic and recreational value are majorly influenced by factors such as phytoplankton concentration, detritus, and nitrogen and phosphorus levels (Alam et al. 2017). Reed vegetation around ponds, crucial for habitat maintenance for biodiversity and recreational activities, contribute to diverse landscape patterns and enhance the visual appeal (Bekefi & Varadi 2007, Sharma et al. 2023). The traditional practice of harvesting reeds for crafting and construction materials contributes to cultural heritage and tourism (Köbbing et al. 2013).

The identified EDS are also presented in Table 2. A deeper understanding of the trade-offs between the benefits of pond aquaculture can result from the estimation of EDS.

Table 2. Classification of model outputs as ecosystem dis-services (EDS)

Definition	Indicator	Model compart-ment	Model element /process	Explanation
Regulatory disservice: Local climate destabilization by increase of greenhouse gas concentrations.	Released CO_2	Land reed	Soil respiration	CO_2 released by soil to the atmosphere
		Land reed + Pond reed	Plant respiration	CO_2 released by plants to the atmosphere
		Pond	Desorption	CO_2 released by pond water to the atmosphere
Regulatory disservice: Release/dispersion/emission/Dispersal from ecosystems.	Emission of excess nutrients (N, P) and toxic gases (CO_2)	Pond	Wastewater and biowaste discharge	CO_2, N, and P are released in areas surrounding the pond
Provisioning disservice: natural abiotic ecosystem inputs	Vol. of water used	Pond	Water supply	Amount of water required by the ecosystem from humans to meet water demand deficit

4. CONCLUSIONS AND RECOMMENDATIONS

This work focused on the development of a coupled process-based model, as well as on the process model-based assessment of the environmental impacts and ecosystem services of fishpond aquaculture. The processes of managed pond food web and reed vegetation were investigated, based on the developed model.

A previously developed fishpond model (i.e., "reference model") was improved for much wider application, ranging from more extensive management practices to relatively high intensity types. At the same time work was done on increasing the re-usability aspect of the model. The systematic improvement process also revealed the need of other extensions in the model food web. Finally, the improved model demonstrated up-scalable properties when applied to another fishpond site with very limited field data available. A major limitation in the development of the model was the lack of information on possible sampling and measurement errors occurring during the pilot experiments. It was inferred that to accurately assess measurement errors, the experimental design should include essential, locally distributed parallel samples. However, due to the high cost and manpower demands, using computational models is recommended to aid in experimental planning, either beforehand or alongside experimentation. The model development also faced data related limitations such as missing data, faulty sensors, and incomplete site history also affected accuracy, highlighting the need for comprehensive initial data collection and continuous collaboration between field experts, sampling staff, and model developers.

In the next stage the fishpond agroecosystem was conceptualized as a coupled model of the fishpond food web and reed plant growth to account for material flows between their different horizontal and vertical compartments. Considering the conservational laws-based establishment of environmental interactions, the stoichiometry of components was taken into consideration in the coupled model, consciously. The study found that there is still a lack of consistent stoichiometric data available in the literature, particularly for aquatic plant species. Despite these approximate data, the model demonstrated the applicability of stoichiometric level e.g., in nutrient cycling (between subsystems), nutrient limitations (e.g., in reed) or in trophic interactions (e.g., in the underlying food web in the fishpond). Also, it highlights the need for the underrepresented, but relatively easy and affordable elemental analysis in future work.

The most significant result of the coupled model of the fishpond-reed agroecosystem was the ability to interpret the quantitative environmental interactions of fishpond aquaculture in a clear and comprehensive manner by using unified model elements and linkages that represent the physical, chemical, biological, ecological, environmental, and managerial technological processes involved. The model makes it possible to determine quantitative impacts on the environment and ecosystem services, and to analyze dynamic balances and causal relationships associated with freshwater fishpond system. The designed model also shows an insensitive behavior towards fluctuating initial conditions, thus making it more robust and reliable for decision making.

In this work the architecture of Programmable Process Structures (PPS) was used to construct the fishpond-reed agroecosystem model, which provides the freedom of easy customization. reuse, extension and coupling of different sub-models and systematic incorporation of expert reasoning.

To showcase the use of model simulation to determine quantifiable ES indicators from fishpond aquaculture, the three main categories of the ES i.e., the regulatory services, the provisioning services and cultural services were selected. It was inferred that indicators for certain categories of ES could be calculated directly from the simulations, while other categories, e.g., cultural ES and habitat maintenance services for biodiversity, could be derived using rules based on quantitative simulations. On the other hand, the negative environmental impacts of the fishpond have also been quantified and termed Ecosystem Dis-services

(EDS). The model-based indicator assessment, as the evaluation of the sometimes overlapping, sometimes contradictory ES indicators can be facilitated by the clear overview of the quantitative basis of environmental impacts. Increased reed cover can increase CO_2 sequestration, but not always, due to plant respiration and reed decomposition. Proportional harvesting maintains water space and provides material, while composting recycles nutrients. However, burning reeds wastes biomass and increases greenhouse gas emissions. Some fish farmers leave cut reed in ponds to reduce costs, leading to excess sediment and management problems. Thus, it is recommended to follow a circular pathway in the pond management practices in connection with other land sectors to ensure the sustainability of the system and the optimum delivery of the ES.

Assessments based on the model developed in this study could be used as a decision support tool to determine the appropriate level of management, to design forecasted trails and other training and education purposes. It is important to note that due to several limitations in the model contour and unavailable data, certain factors such as fish predation by cormorants and other birds could not be included in the model. Also, the developed model in its current state is limited in terms of spatial variability but is capable of extension in light of sophisticated measurements.

The approach to ES assessment presented in the study provides a crucial and sound basis for the design of policy and regulatory frameworks that encompass the fishpond aquaculture sector and promote eco-intensification practices. Accurately quantified ES could serve as a valuable input for generating additional income for farmers through payment mechanisms and highlight the importance of the freshwater fishpond aquaculture sector in achieving the EU's blue economy objectives. Better communication of the scientific results could motivate fish farmers to implement additional activities on fish farms in order to fully exploit the ES provided by this scheme.

5. NEW SCIENTIFIC RESULTS

1. My work contributed to improving the functionalities of the previously developed fishpond model by (i) developing an extended pond food web model; (ii) accounting for additional nutrient pools from inorganic fertilizer inputs; (iii) accounting for sedimentation events; and (iv) completing the set of actual local meteorological data and also improving its reusability aspects.

2. Using literature-based data and relationships, and adapting the simplified plant model, implemented in Programmable Process Structures, I developed a growth model for pond reed and terrestrial reed.

3. I constructed and tested a coupled pond aquaculture model, comprising a managed pond food web and reed vegetation.

4. I completed a model-based analysis of the environmental impacts of pond aquaculture under different management scenarios (based on stocking densities, manuring pattern, reed cover management - reed cutting, reed removal, etc.).

5. I have demonstrated the use of quantitative simulations to assess environmental interactions and to calculate indicators of the ecosystem services and dis-services, provided by pond aquaculture.

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7. PUBLICATION LIST

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