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ORIGINAL PAPER

Analysis of the Aquaponic System Sustainability via System Dynamics Modelling – FEW Nexus Approach

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Abstract

Aquaponic systems integrate aquaculture and hydroponics, recycling nutrient-enriched water from fish tanks to grow plants, significantly reducing carbon emissions, water use and production costs compared to other methods. It is considered a sustainable solution for food production, addressing issues such as climate change and eutrophication. Particularly valuable in family farming, it increases the diversity and quality of food, while reducing its environmental impact. However, despite its potential, aquaponics lacks recognition in public policies, making its widespread adoption difficult. Quantifying its benefits is crucial for strategic planning and the formulation of policies to support family farming and the transition to sustainability, in line with global objectives. Therefore, there is a need to comprehensively quantify the benefits of aquaponics, particularly in terms of the Food-Energy-Water (FEW) nexus, to support decision-making and policy formulation for sustainable agriculture. The nexus concept encompasses highly complex systems requiring robust tools capable of analysing the interrelationships between multiple components. Aiming to analyse the degree of sustainability of aquaponics systems on family property in the FEW nexus context, a System Dynamics Modelling (SDM) coupling Socio-economic and environmental indicators was developed. The results obtained demonstrated the efficiency of using SDM as an analysis and support tool for decision-making. Additionally, they prove the environmental viability of food production via aquaponic systems.

Keywords Aquaponic · Food-energy-water · Sustainability · System dynamics modelling · Agriculture

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Introduction

Aquaponics is an integrated production system that combines elements of aquaculture and hydroponics, where nutrient-enriched water from fish tanks is used for plant growth while saving resources [1, 2]. The system significantly reduces water consumption and production costs compared to hydroponics and aquaculture, as well as compared to other animal protein production systems [3].

Aquaponic system have been proposed as a sustainable solution for food production, reducing resource consumption, as approximately 98% of aquaculture effluents are recycled daily, mitigating the discharge of effluents into the environment [4–6]. Additionally, this system represents a sustainable approach revolutionizing traditional agriculture in response to challenges such as soil fertility and natural resource losses, reduced fertilizer usage and greenhouse gas emissions [7, 8].

Therefore, it can be an environmentally favorable system, especially considering nexus approaches such as in the Food-Energy-Water (FEW) case. Since the World Economic Forum [9], the FEW Nexus approach has been regarded as a conceptual and theoretical tool for understanding the challenge of transitioning to sustainability. The approach has the capacity to consider the interdisciplinary and multiscale objectives of the FEW dimensions. This is supported by the urgency to achieve resilience in the food-energy-water components in light of climate change [10].

The popularity of aquaponics farming is on the rise as it seeks to fulfil rising consumer needs. Projections from the Aquaponics Market Forecast (2020–2025) anticipate demand to surge, with a compound annual growth rate (CAGR) estimated between 14.5% and 15.5% by 2025. Among the frequent integration in aquaponics farming are vegetables as spinach (*Spinacia oleracea*), basil (*Ocimum basilicum L*), okra (*Albelmoschus esculentus*) and pangasius/catfish (*Pangasianodon hypophthalmus*) [11–13].

Aquaponics can be an alternative for diversifying production in family farming, which in Brazil is responsible for more than 70% of food production for the domestic market [14]. In recent years, aquaponics farming has garnered increased public attention, particularly in urban settings, reflecting a broader trend towards achieving higher productivity with limited resources. This transition has propelled it from small-scale operations to commercialization [15].

In the case of the city of São Paulo, the most populous city in Brazil with a metropolitan region with around 21 million inhabitants, the demand for food production is paramount. Like many cities in Brazil and around the world, São Paulo has a green belt around it, responsible for the conservation of biodiversity, water supply, leisure, temperature control and food production. However, the expansion of urbanization in recent years has been affecting food production in the green belt, which is responsible for supplying at least 70% of vegetables for the metropolitan region.

The advance of urbanization under the green belts highlights the need to develop public policies aimed at reducing socio-environmental problems and strengthening food security in large cities. Particularly in the Brazilian context, it was identified during the development of this study the absence of public policies focused on sustainability transitions that encompass aquaponic systems. For example, none of the existing payment schemes for environmental services in the country consider aquaponics; there is also no certification process for products, and there are no specific government programs for purchasing their products. Consequently, aquaponics ends up being undervalued due to the lack of detail regarding the real gains obtained by this productive system.

This fact is supported by the urgency to achieve the resilience of food-energy-water components in light of climate change [16]. The quantification of interactive relationships between components of complex systems, as a FEW nexus approach, allows analyses of potential trade-offs in scenarios that have multiple attributes. These analyses could be provided by the System Dynamics Modelling (SDM) tool application [17, 18]. The SDM is considered a robust methodology to analyse and understand risk scenarios, prioritizing actions that consider uncertainty, optimize offsets, and reflect institutional capacity [19].

Considering the application of modelling tools for aquaponic systems, there is a scarcity of mathematical models dedicated to the study of system processes [20]. Most studies that employ mathematical modelling in aquaponics aim to optimize optimal growth conditions for plants and fish, such as studies developed by Goddek et al. [21].

Therefore, the aim of this study is to analyse the aquaponics systems in terms of the FEW nexus applying as a case study a family farming scale, in a delimited area in the green belt of São Paulo. Due to the complexity of the interrelationships between the components of the FEW nexus, the objective is to analyse the sustainability of the aquaponic system through SDM simulations for socio-economic-environmental parameters previously selected.

Material and Methods

Research Design

The understanding of complex problems via simulation and modelling tools occurs through the organization of consecutive steps. In order to explore this study and reach the proposed objectives, the research design was carried out in three stages (Fig. 1), starting with the development of the causal loop diagram (CLD) for the FEW nexus according to Dal Poz et al. [22] and the flowchart of the company's process, followed by the characterization and, ending with the model development.

System Dynamics possesses the capacity to simulate modelling aimed at addressing complex problems. Typically, the analysis of complex systems begins with the mapping and representation of components to develop conceptual maps that facilitate the capture, organization, and refinement of the understanding of synergies between systems

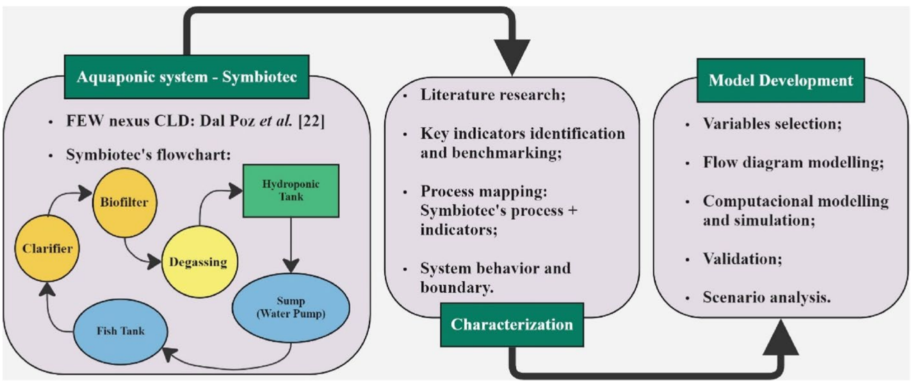

Fig. 1 Research Design for SDM-Aqua model development

components. Causal loops diagrams (CLD) serve as examples of concept maps utilized to illustrate complex system dynamics [16]. This approach focuses on describing fundamental information such as directionality and positive or negative impacts, rather than specific mathematical relationships [10], providing a foundation for developing models within the system dynamics framework.

System Dynamics Modelling (SDM) enables the quantification of interactive relationships among components of complex systems, allowing for the analysis of potential trade-offs in scenarios with multiple attributes [17, 18]. SDM is recognized as a robust methodology for analysing and understand risk scenarios, prioritizing actions that account for uncertainly, optimize offsets, and reflect institutional capacity [19].

Decision-making in food production encompasses non-market or political market situations, along with the intricacies between technological and environmental components, Hence, the decision-making framework requires an expanded list of decision-makers for the implementation of more sustainable systems [23]. In addition to the main stakeholders' opinions, in the design and discussion of the research results, we considered the integration and participation of the different institutions involved during the decision-making process, such as river basin committees, food safety councils, producer and consumer associations, agroecology networks, energy and water companies and agencies, as well as governments bodies.

The process constituting the FEW nexus necessitate the use of strategies such as simulation of predictive scenarios for effective decision-making. According to Li et al. [24], scenario analysis employing simulation tools optimized by programming codes can enhance modelling interaction and generality. This approach has been employed by several studies in FEW nexus modelling across various configurations and food production in recent years.

Characterization of the Study

As a basis for this study, the production system from the company Symbiotec—Aquaculture and Integrated Production Systems Ltd. was used, developed to simulate aquaponic production in a family farming model, with the minimum size necessary for the subsistence of a family. The company is located in the municipality of Piracicaba/SP, Brazil. The system is made up of fifteen independent and similar modules, each module consisting of a fish farming tank with a capacity of 500L, coupled to mechanical and biological filtration compartments for water treatment and, subsequently, to a cultivation bed. Hydroponic with $2m^2$ of surface area and a water column of 25 cm, with a production capacity of 32 vegetable seedlings each. Hydroponic cultivation is of the DFT (Deep Film Technique) type, also called floating, in which the vegetables are arranged on extruded polystyrene plates with the roots completely submerged in water, under constant aeration. After passing through the hydroponic beds, the water is recirculated to the fish tank, maintaining a 24-h recirculation system.

The model, considering the Symbiotec´s data, was designed for the region known as the "green belt," composed of regions of the mega metropolis of São Paulo. The green belt is located at the edge of the Atlantic Forest, evidencing the complexity of the analysis of the FEW (Food-Energy-Water) nexus.

The characterization phase was dedicated to establishing the system to be studied, defining what should be considered in it so that the model development phase could be performed with due accuracy. The choice for using System Dynamics was based on its ability to simulate modelling that can deals with complex problems. The establishment of benchmarking was carried out previously based on literature and technical protocols considering collected data from production systems and/or international protocols [22]. The benchmarking rule (Table 1) is composed of five levels, in which the pessimistic and optimistic profiles are sub classified into level A-B and D-E, respectively.

The indicators in question are:

- Land Use Earnings—LUE (R$/m^2): represents the average profitability of horticulture in rural properties (unit of analysis) [22];
- Land Social Development Index—LSDI (0–1): developed in partnership with stakeholders, consisting of five sub indicators, (i) Community Supported Agriculture Index—CSAI; ii) Land Use Degree—LUD; iii) Demographic Index of Rural Dependency—DIRD; iv) Ecosystem Services Index—ESI, v) Rural Property Income—RPI [22];
- Trophic State Index—TSI (0–67): used in the measurement of the eutrophication process, enabling the evaluation of water quality regarding nutrient enrichment and its effect on the development of algae/microalgae [25, 26];
- Water Footprint—WF (L/$kg_{product}$): considered a comprehensive indicator of the appropriation of water resources, it represents the volume of water used in production and measured along the entire production chain [27];
- Carbon Footprint [CF] ($kg_{CO_2\ eq}$/month): measure of the total amount, in mass unit, of direct (scope 1) and indirect (scope 2) greenhouse gas emissions [28]. The quantification of this indicator is generally used in studies of mitigation of global warming due to food production.

The Fig. 2 shows a detailed flowchart representing the Symbiotec's pilot plant (aquaponic system) for food production, in this case Tilapia (*Oreochromis niloticus*) as fish and lettuce (*Lactuca sativa*) for vegetables. The process flowchart served as the basis for the development of the SDM-Aqua model for a for the implementation of aquaponics on a hypothetical property located in the green belt of the city of São Paulo designed by. In addition to the production process, the flowchart was developed considering the

Table 1 Socio-economic-environmental indicator's benchmarking

Benchmarking				
Pessimistic (level A)	Pessimistic (level B)	Neutral (level C)	Optimistic (level D)	Optimistic (level E)
Land Use Earnings (LUE)—(R$/m^2)				
LUE ≤ 41.3	41.3 < LUE ≤ 48.8	48.8 < LUE ≤ 56.3	56.3 < LUE ≤ 63.8	63.8 < LUE
Land Social Development Index (LSDI)				
0 ≤ LSDI ≤ 0.2	0.2 < LSDI ≤ 0.4	0.4 < LSDI ≤ 0.6	0.6 < LSDI ≤ 0.8	0.8 < LSDI ≤ 1
Trophic State Index (TSI)				
TSI > 67	TSI ≥ 67	63 < TSI ≤ 59	59 < TSI ≤ 52	TSI < 52
Water Footprint (WF)—(L/$kg_{product}$)				
WF ≥ 740	740 < WF ≤ 580	580 < WF ≤ 420	420 < WF ≤ 260	WF < 260
Carbon Footprint (CF)—(kg CO_2eq/m^2)				
0.69 < CF	0.69 ≤ CF ≤ 0.52	0.52 < CF ≤ 0.35	0.35 < CF ≤ 0.18	CF < 0.18

Dal Poz et al. [22]

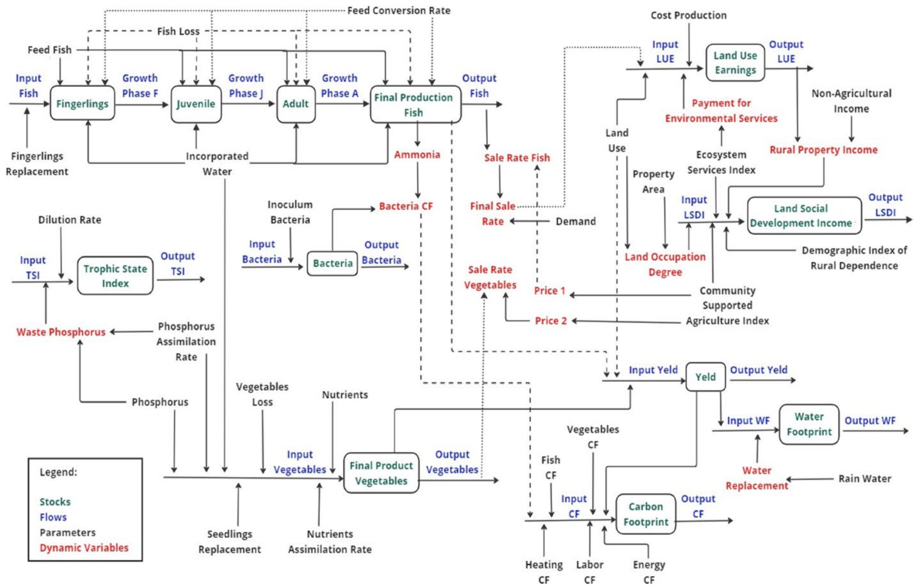

Fig. 2 Flowchart of aquaponics system

Socio-economic-environmental indicators and the respective system interrelations, with the purpose of analysing strategies and/or public policies of interest to the FEW nexus.

The socio-economic-environmental indicators are called stocks, and the parameters and/or dynamic variables represent the interference of the environment under the indicators, showing the positive and/or negative influences between the indicators and the components of the system.

Model Development

The SDM-Aqua model (Fig. 3) was developed in Anylogic® *University* 8.7.7. The systems represent the aquaponic system integrating fish and vegetable production on a scale of $200m^2$. Table 2 presents the model components it the respective input data and equations and respective sources.

Data referring to the production process were from Symbiotec company. The equations used were developed by the SP in Natura Laboratory team or, obtained from a secondary source (literature). The databases of the Center for Meteorological and Climatic Research Applied to Agriculture [38], Center for Advanced Studies in Economics Applied [38] and State Water Resources Fund [39] were used for climatology from Baixo Tietê Basin, products market (fish and vegetables) and water resources data, respectively.

The causality analysis (Table 3) between indicators and system components represents relevant strategies or policies implemented in the transition to a more sustainable system. However, stands out that due to the complexity of the system studied, not all possible relationships were studied.

For the indicators being studied, predictive scenarios were considered for a period of 10 years (120 months). Scenario 1 represents the real state of the production process, that is,

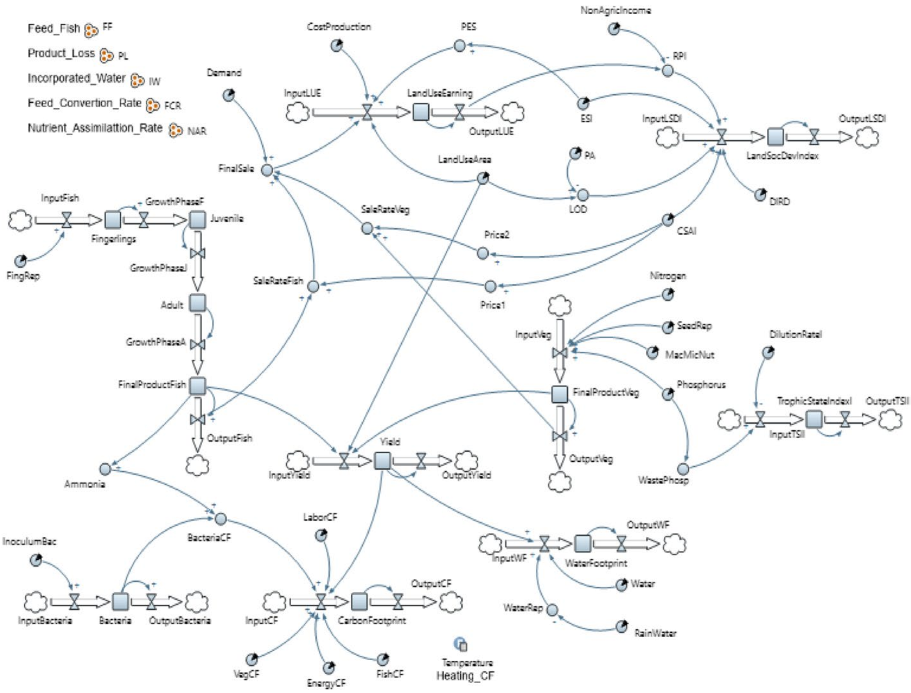

Fig. 3 SDM-Aqua model that represents the process for the aquaponics system

processes that do not have the implementation of sustainable strategies. Scenarios 2–4 present the adoption of technologies or public policies identified as sustainable.

In addition, Scenarios 5–6 were evaluated for the TSI and WF indicators, aiming to simulate environmental events, specifically a prolonged water crisis. The hypothetical simulation of a period of climate crisis considered a rainfall deficit of 30% and a dilution rate of the Baixo Tietê Basin [39] constant in its minimum mean.

- Scenario 1: null CSAI and ESI;
- Scenario 2: random CSAI and ESI with 1%/month implementation;
- Scenario 3: random CSAI and ESI with 5%/month implementation;
- Scenario 4: random CSAI and ESI with 10%/month implementation;

The predictive scenarios were statistically evaluated by analysis of variance (ANOVA) for 95% significance, and the R programming language was used in the production of the graphs. The ANOVA statistical technique, used to perform comparisons between three or more groups in independent samples, met the statistical purposes since the indicators (stocks) are influenced by two or more components (parameters and/or dynamic variables), showing the needs to evaluate the degree of influence on causal relationships.

Table 2 Components and input data of the SDM-Aqua model

Parameter/(Configuration)	Value/Equation
Community Supported Agriculture Index—CSAI (randomly)	0–1.0
Cost Production	R$ 1151.66/month
Demand (seasonal event)	0.75–0.95 (70–100%)
Dilution Rate (seasonal event) [29]	12.4–56.9 m^3/s
Demographic Index of Rural Dependency—DIRD	0.2
Energy Carbon Footprint [30]	4.13 $kgCO_2e$/month
Ecosystem Services Index—ESI (event)	0.0–0.8
Feed Convection Rate (collection FCR)	[(0) 1.1, (1) 1.3, (2) 1.5, (3) 1.8]
Feed Fish (collection FF)	[(0) 4.9, (1) 12.9, (2) 100.8, (3) 405]
Fingerlings Reposition	0.89 kg/month
Fish Carbon Footprint [31]	0.073 $kgCO_2e$/month
Heating Carbon Footprint	0.0005 $kgCO_2e$/month
Incorporated Water (collection IW)	[(0) 3.67, (1) 10.58, (2) 68.35, (3) 264.6, (4) 540]
Inoculum Bacteria	0.03 kg
Labor Carbon Footprint [32]	0.0075 $kgCO_2e$/month
Land Use Area	200 m^2
Macronutrients-Micronutrients –MacroMicroNut- [33]	2.57 kg/month
Nitrogen/N (event) [34]	67.14 kg/month
Non Agriculture Income	R$ 1100.00/month
Nutrient Assimilation Rate (collection NAR)	[(0) 25.9, (1) 8.7, (2) 1.39]
Property Area—PA	400 m^2
Phosphorus/P^2 (event)	62.33 kg/month
Product Loss (collection PL)	[(0) 0.07, (1) 0.03, (2) 0.15]
Rain Water (seasonal event)	0–1500 L/month
Seed Reposition	1 kg/month
Vegetables Carbon Footprint [35]	0.14 $kgCO_2e$/month
Water—total volume	40500 L
Dynamic Variable	Value/Equation
Ammonia	0.00007 * FinalProductFish
Bacteria Carbon Footprint [36]	(Ammonia * 0.1) * Bacteria
Final Sale Rate	(SaleRateFish + SaleRateVeg) * Demand
Land Occupatin Degree—LOD	LandUseArea/PA
Payment for Environment Services—PES	(0.1 * ESI)/12
Price 1	(8.0 * CSAI) + 6.3
Price 2	(3.07 * CSAI) + 3.74
Rural Property Income—RPI	OutputLUE/(NonAgricIncome * OutputLUE)
Sale Rate Fish	Price1 * OutputFish
Sale Rate Vegetables	Price2 * OutputVeg
Wast Phosphorus	Phosphorus -PhospAssRate
Water Rep—Reposition	(IW.get(0) + IW.get(1) + IW.get(2) + IW.get(3) + IW.get(4))—RainWater
Flux	Value/Equation
Growth Phase A	Adult
Growth Phase F	Fingerlings

Table 2 (continued)

Growth Phase J	Juvenile
Input Bacteria	InoculumBac
Input Carbon Footprint	((EnergyCF + BacteriaCF + FishCF + VegCF)/Yield) + LaborCF + (Temperature (getMonth() + 1) < 13?0.0005:0)
Input Fish	FingRep
Input Land Social Development Index [22]	(RPI + LOD + ESI + DIRD + CSAI)/5
Input Land Use Earnings [22]	((FinalSaleRate—CostProduction) / LandUseArea) + PES
InputTSI	WastePhosp/DilutionRateI
Input Vegetables	(SeedRep + (Nitrogen/NAR.get(0))) + (Phosphorus/NAR.get(1)) + (MacMicNut/NAR.get(2)) + (IW.get(4))—(PL.get(2))
Input Water Footprint	(WaterRep + Water)/Yield
Input Yield	(FinalProductFish + FinalProductVeg) / LandUseArea
Output Bacteria	Bacteria
Output Carbon Footprint	CarbonFootprint
Output Land Social Development Index	LandSocDevIndex
Output Land Use Earnings	Land Use Earning
Output Trophic State Index	TrophicStateIndex
Output Water Footprint	WaterFootprint
Output Yield	Yield
Output Fish	FinalProductFish
Output Vegetables	FinalProductVeg
Output Yield	Yield
Stock	Value/Equation
Adult	((GrowthPhaseJ)—(GrowthPhaseA)) + ((FF.get(2)/FCR.get(2)) + (IW.get(2))—(FL.get(1)))
Bacteria [37]	((1.08 * 30) + InputBacteria)—OutputBacteria
Carbon Footprint—CF	InputCarbonFootprint—OutputCarbonFootprint
Final Product Fish	((GrowthPhaseA)—((OutputFish)) + ((FF.get(3)/FCR.get(3)) + (IW.get(3))—(PL.get(1)))
Final Product Vegetables	(InputVeg + IW.get(3))—OutputVeg
Fingerlings	((InputFish)—(GrowthPhaseF)) + ((FF.get(0)/FCR.get(0)) + (IW.get(0))—(FL.get(0)))
Juvenile	((GrowthPhaseF)—(GrowthPhaseJ)) + ((FF.get(1)/FCR.get(1)) + (IW.get(1))—(FL.get(1)))
Land Social Development Index—LSDI	InputLSDI—OutputLSDI
Land Use Earning—LUE	InputLUE—OutputLUE
Trophic State Index—TSI [26]	(10 * (6—((0.42—0.36 * (log(InputTSI))/0.69)))—20)—OutputTSI
Water Footprint—WF	InputWaterFootprint—OutputWaterFootprint
Yield	InputYield—OutputYield

Table 3 Causality analysis design for predictive scenarios

Indicators	Causality analysis
LUE, LSDI	The effect of the implementation of Payment for Environmental Services (PES) and Community Supported Agriculture (CSAI) was evaluated. PES is a practice that is being conducted by international development banks, such as the World Bank [40]. The input data for Ecosystem Service Index (ESI) followed the methodology used by the Inter-American Development Bank (IBD) and adapted by the Public Selection Notice PSA no. 006 [41] by the Foundation of Scientific and Technological Enterprises (FINATEC), the Secretariat of the Environment of the State of São Paulo, and the Forestry Foundation of the State of São Paulo. The programs do not establish ESI standards for aquaponics systems, so a value of 0.8 was implemented in order to hypothetically classify it between conventional and agroecological systems. The CSAI refers to direct sales from producer to consumer, hypothetically resulting in greater gains from land use. Due to the lack of historical data and national studies on Community Supported Agriculture, the input data were programmed in random mode.
TSI	The strategy of waste phosphorus reduction used in the production process was adopted as proxy of the ESI. Since the eutrophication process is affected by climatic factors, such as rainfall that influences the flow of water sources, the parameter Dilution Rate was programmed simulating the seasonality of the region under study [39].
WF	The proxy for the ESI adopted was the reduction of the water footprint, represented by the reuse of rain water during rainy periods.
CF	The ESI strategy considered replacing the use of the traditional energy source with alternative sources (solar/wind energy).

Results and Discussion

Socioeconomic and Environmental Indicators Analysis

The Fig. 4 presents the predictive scenarios for the socioeconomic and environmental indicators and their respective benchmarking for the aquaponics system production.

The results obtained for the simulation of scenarios for the LUE indicator (Graph I) indicate that the implementation of CSAI (scenarios 2–4) directs food production by the aquaponic system to higher sustainability levels when compared to scenario 1 (benchmarking level A), achieving a neutral level (B) and sometimes at level (C). Since the CSA parameter was programmed randomly, the influence of the parameter on land use gains is clearly observed during months with high CSA activities. Additionally, scenarios 2–4 do not demonstrate a significant difference, resulting in overlapping of the values obtained.

However, it is observed that the implementation of ESI strategies does not significantly influence the results. Specifically, for this study, ESI represents a proxy of the Payment for Environmental Services (PES) policy, simulated hypothetically since aquaponics is not covered by Notice nº 006/2018 [41].

The monetary values received by family producers do not influence the sustainability of the property in any way, presenting a marginal effect on LUE. Similar results were obtained previously for the simulation of the effects of PES on food production for conventional and organic crops for family production in Brazil [42].

In general, Payments for Environmental Services (PES) are often implemented on a large scale or in different contexts, which can compromise their effectiveness. To deal with these limitations, some studies suggest the implementation of differentiated payments for

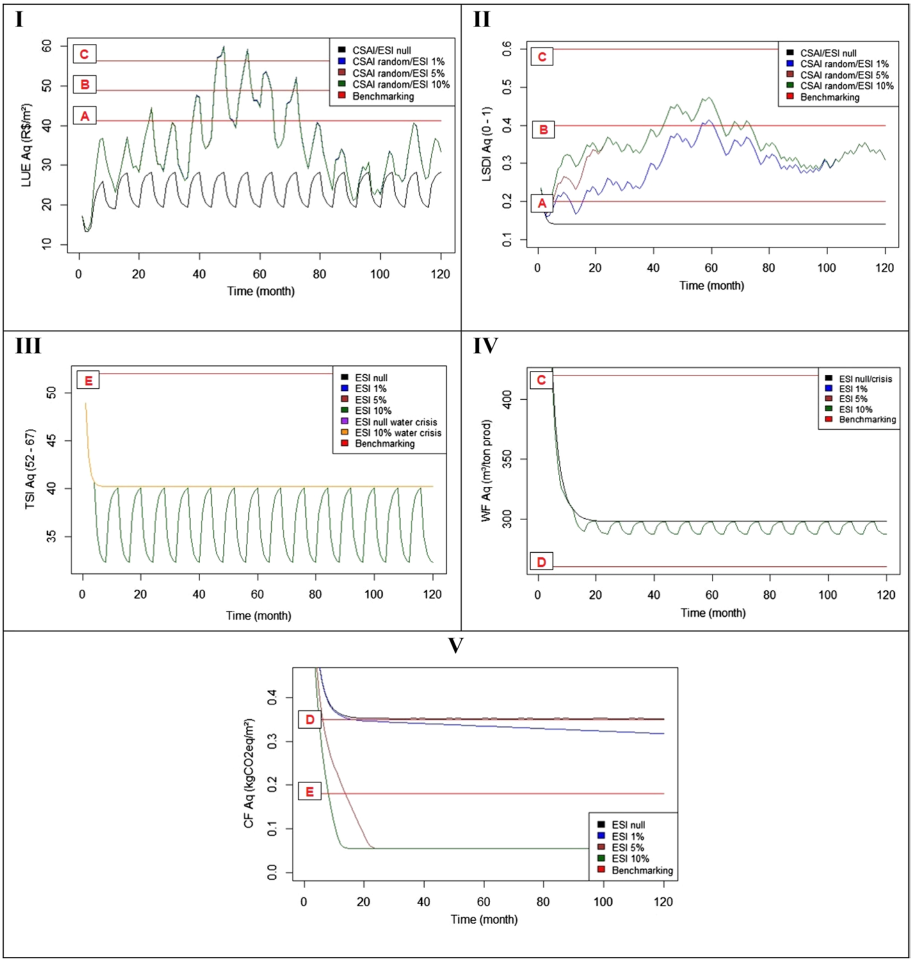

Fig. 4 Results from predictive scenarios from SDM-Aqua model

environmental services (DPES), which take into account the specific conditions of each case or region. This model is more efficient in achieving conservation objectives, offers greater social and environmental benefits, and, therefore, could be applied to an aquaponics system [43].

Graph II presents the result for the LSDI indicator and the causality relationship with CSAI and PES policies. There is a clear positive effect in the implementation of such policies for all tested scenarios; however, a better sustainability level is observed for scenarios 3–4 which additionally show no difference starting from the 20th month. However, even under better conditions, the results point to achieving neutrality (level C) as the best conditions.

The behaviour of the simulations is similar to that observed for the LUE indicator, confirming that the current Brazilian PES policy is not immediately attractive to producers when considering direct financial returns. However, properties included in PES programs receive technical support aimed at improving productivity, sales strategies, product valuation, and producer training, possibly resulting in indirect gains that, for the study in question, were not possible to quantify.

According to Verma et al. [16], aquaponics, when approached in terms of the FEW nexus, specifically meets the United Nations' sustainable development objective by embracing the concept of 'circular bio-based economy'. The results obtained highlight the importance of adopting simulated public policies to meet various SDGs' targets.

The analysis for the TSI indicator (Graph III), which represents the level of eutrophication in water bodies, demonstrates that the behaviour of aquaponic systems is located at the highest level of sustainability (benchmarking level E), according to metrics for the State of São Paulo [25].

Simulations shows that the individually analysed pilot plants do not compromise water quality, even in a scenario described as neutral, representing the absence of ESI strategies. However, additional studies are needed regarding many of these units and the effect of seasonal tank cleaning routines, as well as the potential escape of effluents into water bodies for the Baixo Tietê Basin.

Therefore, the results prove the feasibility of using these systems in the production of fish and vegetables. Particularly in the case of aquaculture, which is currently the most rapidly expanding sector within agriculture globally and is projected to fulfil 54% of the anticipated 200 million tons of fish demand by the year 2030, it is evident that this industry possesses significant potential to influence the environment on a large scale [44]. Ultimately, aquaponics, incorporating a hydroponic element and thus eliminating the need for soil, presents an opportunity for efficient utilization in controlled urban environments. This approach can effectively address production challenges stemming from land scarcity resulting from urbanization [45].

The results observed in Graph IV, for the WF indicator, demonstrate that the aquaponic system exhibits a sustainable profile, even in the case of non-implementation of rainwater reuse as an ESI strategy. It is observed that the aquaponic system leads to the second level of sustainability, consistently positioning results between benchmark D and C (optimistic level) throughout the simulated period.

Aquaponic systems enhance water use efficiency compared to traditional Recirculating Aquaculture Systems (RAS), as they utilize water that would otherwise be lost in waste filtration for plant growth. Various studies indicate that aquaponic systems typically consume between 0.3% and 5.0% of the total system water per day [46]. In contrast, basic recirculating hydroponic systems often necessitate complete nutrient replacement every 2–3 weeks, leading to the renewal of water volume [46, 47].

The analysis of the carbon footprint (Graph V) for the studied scale demonstrates that CO_2eq emissions fall within the neutral range for the pessimistic simulation, meaning the full use of electricity from the distribution system. Examining predictive scenarios, a slight reduction in CF is observed for scenario 2, directing the indicator to a degree just below neutrality (level D). However, for scenarios 3–4, CF is drastically reduced, reaching the point of highest sustainability (Benchmarking E). We can conclude that the implementation of ESI results in zero emissions of CO_2eq, demonstrating the viability of the strategy for the studied production modes.

Nowadays, the call for rapid adjustments in our habits and behaviours to mitigate the environmental and climate effects of food systems is clear, as is the case in the European Union (EU) [48, 49]. The adverse environmental effects of meat consumption are widely recognized and fish presents itself as a viable alternative, as global aquaculture was responsible for only around 0.49% of anthropogenic greenhouse gas (GHG) emissions in 2017 [50], significantly lower than land-based livestock farming, which resulted in around 15% of emissions [7]. The results obtained for CF agree with the literature demonstrating the environmental benefits of aquaponic systems.

Additionally, metropolitan regions have characteristics that can pose obstacles to both food systems and their sustainable development. Among these particularities, we can mention high population concentration, high consumption of resources, critical infrastructure, and environmental impacts concentrated in small areas [51, 52]. Especially for food systems, places of production and consumption have become increasingly disconnected due to the process of globalization and industrialization in the sector [53]. Urban space opportunities emerge as a result of comprehensive urban planning and better integration of various sectors at a regional level. These opportunities have the potential to decrease the per capita environmental footprint, foster synergistic enhancements within the urban framework, and re-establish connections between cities and their surrounding rural areas [7, 52].

Conclusions

The application of the system dynamics modelling tool in the analysis of the sustainability of the aquaponics system for the FEW nexus proved to be robust and efficient for the indicators in question. Therefore, points the viability of the SDM as tool as support for decision-making and development of public policies.

Regarding aquaponics, a system considered worldwide as an option for sustainable food production, analyses of predictive scenarios confirm the feasibility of its implementation in metropolitan regions. It emphasizes the need for public policy, in parallel with additional studies about socio-economic and environmental parameters, addressing the scheduling of production to meet the high demand for food in regions such as the mega-metropolis of the city of São Paulo.

Among the possible recommendations for public policies, we highlight the importance of considering aquaponics in family farming support and finance programs, payments for environmental services, and public purchases for school meals, in addition to the carbon credit market. A certification system that attests to the sustainability and sanity of the aquaponic system would also be an alternative to increasing the sales value of the products.

However, it is necessary to highlight the need for additional studies that consider the scaling of food production plants via aquaponics and its consecutive impact on the economic, social and environmental spheres. As the use of system dynamics modelling proved to be viable in the analysis of sustainability for the scale studied, it is concluded that its use for scaling studies and support for decision-making can be an alternative in the adoption of emerging technologies and, for the development of public policies aimed at the transition to sustainability.

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Declarations

Competing Interests The authors have no competing interests to declare that are relevant to the content of this article.

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