Efficiency tests for screening production strategies in a lettuce-juvenile tilapia aquaponics system in Brazil

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Abstract

This article assesses strategies for managing the economic returns to an aquaponics production system with joint products of lettuce and tilapia. Experimental data from Brazil that varied fish stocking density and the fish feeding rate are analyzed using nonparametric efficiency testing methods to identify potentially profitable technologies and their sensitivities to prices of inputs and outputs. Plants and fish production are symbiotic in an aquaponics system, with fish waste providing nutrients for plant growth and plants helping maintain water quality for the fish via filtration. The optimal input/output mix among alternatives is identified, and sensitivity analysis is used to assess the price ranges around recent market conditions (0.18 R$/tilapia fingerling, 2.8 R$/kg for fish feed, 20 R$/kg for juvenile fish and 1.57 R$/kg for lettuce) over which that technology choice remains optimal. The configuration of production controls is robust to price changes. Results show that at low fish stocking densities (100 fish/m^3), the effluent in the water provides insufficient nutrients to plants. In addition, early lettuce harvests (before 26 days) are generally less efficient than treatments that allow more time for plant growth. Sensitivity analysis indicates that the optimality of the identified configuration of production controls is robust with respect to input and output prices.

Keywords: Aquaponics, non-parametric efficiency analysis, stocking density, feeding rate, tilapia and lettuce production.

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Declarations

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Competing Interests

No potential financial or non-financial conflict of interest was reported by the author(s).

Ethics approval

This research was certified by the Committee on Ethics in the Use of Animals – CEUA (acronym in Brazilian Portuguese) of Faculty of Agricultural and Veterinary Sciences, UNESP – Jaboticabal/SP- Brazil, on February 13, 2020 – protocol n.001122/20 – under the responsibility of Professor Dr. Maria Célia Portella. The research is in accordance with the precepts of the Brazilian federal law nº 11794, October 8, 2008.

Data Availability Statements

All data generated or analysed during this study are included in this published article and its supplementary information files (Appendix B).

Code availability

Not applicable to this research.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Roberto Manolio Valladão Flores, Paul V. Preckel, Kwamena Quagrainie, Nicole Olynk Widmar, Sara M. Pinho, Thais Castelo Branco and Manoel Xavier Pedroza Filho. The first draft of the manuscript was written by Roberto Manolio Valladão Flores and all authors commented on various versions of the manuscript. All authors read and approved the final manuscript.

1. Introduction

Aquaponics involves the joint production of fish from aquaculture and plants from hydroponics in an integrated growing system, where the waste from fish production is converted by bacteria into useful nutrients for plants (Bosma et al. 2017). It is also a promising sustainable food production method since integrating aquaculture and hydroponics techniques allows aquaponics to address some deficiencies of both systems (Goddek et al. 2015). Most of commercial aquaponics production is done in greenhouses or indoors in a controlled environment, combining techniques and tools from both hydroponics and aquaculture systems (Love et al. 2015). The approach to plant fertilization could allow aquaponic vegetable production to be considered organic, and can attract higher prices and provide economic incentives for commercial aquaponics production (Quagrainie et al. 2018).

Aquaponics production continues to attract interest around the world, and researchers are trying to understand its economic viability. A general literature review by König et al. (2018) showed aquaponics as an emerging joint production system and that tilapia was the most frequent fish species used. In a survey of aquaponics enterprises in the United States, tilapia was also identified as the most frequently selected species for fish farming and that less than one third of tilapia farming enterprises are economically viable (Love et al. 2015). Knaus and Palm (2017) investigated the effect of juvenile tilapia and carp on plant (lettuce, cucumber and tomato) growth in coupled aquaponic units using a metric called Aquaponic Growth Factor (AGF), which describes the combined fish/plants growth performance. The authors concluded that the best combinations were tilapia with tomato and carp with cucumber.

Brazilian aquaponics literature is incipient; while some aquaponics production experiments have been conducted, there are only a few relevant economic studies (Hundley and Navarro 2013; Braz Filho 2014). Most Brazilian aquaponics research has focused on tilapia and vegetable production (Carneiro et al. 2015). Pinho et al. (2020) evaluated the aquaponics production of tilapia juveniles and lettuce using biofloc effluents.[1] This analysis indicated economic viability for a system

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[1] Biofloc effluents technology corresponds to the "growth of microorganism in the culture medium, benefited by the minimum or zero water exchange. These microorganisms (biofloc) have two major roles: maintenance of water quality, by the uptake of nitrogen compounds generating 'in situ' microbial protein; and nutrition, increasing culture feasibility by reducing feed conversion ratio and a decrease of feed costs." (Emerenciano et al., 2013)

that produces a minimum of 63.5% plants that are visually suitable for marketing (Pinho, 2018). Aquaponics activities are just beginning to attract some interest in Brazil, and the lack of interest so far is due to several factors including misinformation, insufficient economic data and high initial investment costs. However, there are successful enterprises in other Latin American countries like Mexico and Chile where aquaponics production was motivated by water shortage problems, similar to conditions observed in some regions of Brazil (Emerenciano et al. 2015).

Although Brazil is known for its rich endowment of freshwater – about 12% of the world's freshwater – this abundance of water is neither spatially nor temporally uniformly distributed (Emerenciano, Gaxiola and Cuzon 2013). Water shortages are critical problems in the agriculture sector and a principal cause of food supply issues in some regions (Lemos and Oliveira 2004). Aquaponics is extremely attractive for areas prone to water shortages, because there is minimal wastewater discharge, and it requires a modest amount of freshwater, mostly for replenishment of water lost due to evaporation and evapotranspiration (Zou et al. 2016). In addition, aquaponics is a clean system that is suitable for all regions, including urban environments (Hundley et al. 2013). Yep and Zheng (2019) reviewed over 529 publications in aquaponics and found that tilapia and dark leafy vegetables are the most successful species for aquaponics. The importance of tilapia for the Brazilian aquaculture sector is reported by Flores and Pedroza Filho (2019), Castilho-Barros et al. (2020) and Flores et al. (2021). The aquaponics literature reports the impact of both stocking density and feeding rate in the growing systems (Nhan et al. 2019; Birolo et al. 2020) and in the production of tilapia in Brazil (Baccarin and Camargo 2005; Rodrigues et al. 2016). The literature also presents some economic analyses of aquaponics (Kodama 2015; Carvalho et al. 2017); however, most of the studies used simple assessments of costs versus benefits and cash flow analysis. Nonparametric efficiency testing methods, which are usually used for assessing the behavior of economic agents (see e.g., Linde-Rahr 2005; Baležentis, Kriščiukaitienė, and Baležentis 2013; Guerrini et al. 2017), are used in this study to identify the set of undominated[2] technologies (production strategies) as specified by the input mix and the resulting output mix (Lin and Shao 2007). The initial assessment assumes only that

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[2] A technology or production strategy is dominated if a linear combination of observed strategies can produce more of the outputs using no more inputs, or can produce as much of the outputs using less inputs.

prices of inputs and outputs are strictly positive (Parman, Featherstone and Coffey 2017). Dominated technologies are never used for an economically optimal production system – other technologies will always produce higher profits. The profit maximizing technology choice will depend on the level of input and output prices.

It appears that there is economic potential for aquaponics activities in Brazil as well as associated environmental benefits given the sustainable characteristics of the production and the water shortages in some regions. Therefore, this article aims to fill the gap in the literature by demonstrating the screening of experimental data focused on alternative production strategies for joint production of lettuce and juvenile tilapia in an aquaponics system using nonparametric efficiency testing. In addition to screening out strategies that are inefficient, we also assess the robustness of the production control settings identified as economically optimal for given prices, to shifts in both input and output prices. These procedures will help to identify aquaponics production systems with good economic potential.

2. Material and Methods

The data for this study were collected from an experiment with tilapia and lettuce conducted at an aquaponics facility at a Brazilian university in July 2019. The experimental design uses 16 producing units, with each unit comprised of: a coupled aquaponics system with one fish tank (380 L useful volume), a 100 L settler tank, a bag filter, a 180 L moving bed biofilter (52.9 m^2 for bacterial attachment), and three plant tanks (60 L useful volume each). Each plant tank has a surface area of 0.42 m^2 allocated across eight lettuce plants. The water was recirculated through all compartments using a Sarlobetter SB100A submersible pump in the biofilter, which also worked as a sump. The diagram of the experiment design is presented in Fig. 1.

[Place Fig.1 near here] **Fig. 1** Diagram of the aquaponics system used in the experiment.

Notes: RFS: radial flow settler. MBBR: moving bed bioreactor (biofilter).

In addition, Fig. 2 shows an example of an experimental aquaponics setup, similar to that used in the experiment. Photographs of the actual setup are presented in Appendix A - Fig. 3, Fig.4 and Fig.5. (Note that the plant tanks in Fig. 2 have a different configuration from the experimental setup being reported. In the diagram, there are 9 plants per tank, instead of 8 plants per tank.)

[Place Fig.2 near here] **Fig. 2** Example of experimental aquaponics device (Pinho et al. 2020).

Four different initial fingerling[3] stocking densities and four feeding rates for a total of 16 input combinations were observed simultaneously in a 30-day experiment. This experimental design was chosen because it has been demonstrated that both variables affect the economic performance of aquaculture production (Losordo and Westerman 1994; Karnatak et al., 2021) and interactions between these two factors could affect economic performance (Losinger et al., 2000). Additionally, it is known that fish feed input affects plant performance in aquaponic systems (Al-Hafedh et al., 2008; Endut et al., 2010). Thus, the combination of these variables was included in the experimental design. Fig. 6 summarizes the experimental design and data collection process. Four levels of fish stocking density were used: 100, 150, 200 and 250 fish/m^3. Fish were fed four times a day with “Guabitech® for Omnivores” dry pellets containing 36% protein. At the beginning of the experiment, the feeding rate was calculated according to the average weight of the fish, and it was recalculated every week based on the recommendations of the feed manufacturer Raguife®, which sets the feeding rate as a % of fingerling biomass and size. The experimental design varied feed input by a percentage deviation from the recommended quantity. The four deviation levels are -3, -1.5, 0 and +1.5%.

[Place Fig.6 near here] **Fig. 6** Summary of inputs variables (experimental design) and the outputs analyzed for lettuce-tilapia aquaponics production

Lettuce output levels (weight in g) were measured every day starting on the 21st day of the experiment using nondestructive testing. Lettuce units with an initial average weight and leaf height

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[3] The initial weight for the fingerlings was 11.47 ± 0.41 g.

of 1.71 g and 4.75 cm, respectively, were introduced in each system with a density of 21.18 plants/m^2. Three lettuce plants per box of plants were randomly selected for measurement each day (the same three units were measured each day). The average of the results for the three measured plants was scaled up to estimate the total output of the producing unit for each day and each setting of input levels (Pinho et al. 2022). Lettuce is one of the most common vegetables produced in aquaponics systems, and previous knowledge provided guidance for the experimental design and the salability classification (Engle 2015, Love et al. 2015).

For fish, the output levels (weight in g) were measured at the 21st, 26th and last day of the 30-day experiment. Weighing the fish every day was not feasible because the fish must be captured, put under anesthesia, weighed and returned to the tank, which stresses the fish and may impair subsequent food intake and growth. Therefore, fish were weighed periodically at days 21, 26 and 30, and fish weight for other days within this range were obtained by linearly interpolating the observed results for each combination of the input levels. The fish were grown to the juvenile stage – 75 g/fish, on average. A sample of 20 fish was measured for each aquaponic production unit during the days designated for measurement. As with the lettuce, the average results for the sample were used to determine the total weight of fish for the entire production unit.

Floating feed was observed for some treatments with feeding rates above the manufacturer's recommendation and lower fish stocking density, indicating some feed wastage. Despite the observation that excess feed was being provided, the experiment was continued at the specified higher level of feed relative to recommendations. The feed waste was removed from the tank to maintain water quality and also because leaving it in the system could clog or damage the aquaponic system.

During the experiment, nitrogen compounds were frequently tested using Labcon colorimetric tests for ammonia and nitrite in each system to ensure that the levels did not become toxic for tilapia. Also, the lettuce units received uniform treatment with respect to magnesium and iron (0.1 mL of magnesium and 0.06 mL of iron were applied to each square meter of plant): these were not considered part of the experimental design.

The costs of inputs were based on the actual prices (0.18 R$[4]/tilapia fingerling and 2.8 R$/kg for fish feed) paid during the winter of 2019. These items were purchased from regular suppliers at normal prices, which is representative of what a producer setting up an aquaponic operation would pay. Revenue for each output was estimated based on the average of prices (20 R$/kg for juvenile[5] fish and 1.57 R$/kg for lettuce[6]) from potential buyers. Hence, there was no variation in prices across treatments in the dataset for either inputs or outputs. The assessments of allocative efficiency applied below do not test behavioral rationality of some economic agent, but rather assess which treatments could be consistent with profit maximization or cost minimization for the given prices.

2.1. Data analysis

A test of output-oriented technical efficiency was applied across treatments from the experimental data and for each output in order to make an efficiency assessment for each treatment. For each treatment, we assess whether more of any output could have been produced using no more input than was used for the treatment and producing as much of the other output as was produced with that treatment. As is common in the nonparametric efficiency testing literature, we assume that any convex combination of the observed treatments yields a technically feasible system of inputs and outputs (see, e.g., Farrell [1957]). The property of constant returns to scale is not assumed due to the fixed size of the aquaponics production units. In addition, all inputs and outputs were normalized to a per year basis. This makes the treatments, which have different production cycles ranging from 21 to 30 days, comparable, with the overall goal of making the annual returns to the production unit as high as possible.

The first nonparametric efficiency test used is a directional test of technical efficiency with respect to a specific output in a multiple output production context. The mathematical formulation is:

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[4] R$ represents the Real, the Brazilian currency. At the time when this document was written R$ 1.00 equaled US$ 0.18.

[5] The average price from potential buyers is 600 R$ for one thousand tilapia juveniles of about 30 g each, which represents an average of 20 R$/kg.

[6] The average price from potential buyers is 5.10 R$ per package with three units of lettuce. Then, the number of lettuce saleable units (according to size and color) produced in the experiment is multiplied by the lettuce unit price (1.70 R$), summed over all treatments and divided by the sum of lettuce weights over all treatments to get the average price of 1.57 R$/kg for lettuce.

$$\text{maximize} \quad \tau \tag{1}$$

$$\text{subject to:} \quad \sum_{i=1}^{I} u_{\tilde{k}i}\lambda_i \geq u_{\tilde{k}0}(1+\tau) \quad \text{for one specific output } \tilde{k}, \tag{2}$$

$$\sum_{i=1}^{I} u_{ki}\lambda_i \geq u_{k0} \quad \text{for every output } k, \tag{3}$$

$$\sum_{i=1}^{I} x_{ji}\lambda_i \leq x_{j0} \quad \text{for every input j, and} \tag{4}$$

$$\sum_{i=1}^{I} \lambda_i = 1,\ \lambda_i \ \geq 0, \tag{5}$$

where *k* indexes outputs, *j* indexes inputs, *i* indexes treatments u_{ki} is the level of output *k* for treatment *i*, x_{ji} is the level of input *j* for the treatment *i*, λ_i is the convexity weight for the treatment *i*, $\tilde{k}$ is the specific output whose efficiency is being tested, and τ is a scalar variable to be maximized. The subscript 0 on u_{k0} and x_{j0} denotes the output/input data for the treatment being tested. In the output constraints, τ scales up the output of the specific output whose production efficiency is being tested. When this test is applied to an inefficient treatment, the optimal objective value will be greater than 0. A value of 0.1, for example, indicates that the treatment could have produced 10% more of output $\tilde{k}$ than what was observed to be produced given the level of inputs used and requiring that at least as much of the other outputs must also be produced.

The second test is similar to the first test but instead of output, it was a test of input-oriented technical efficiency. This test assesses, for each treatment, whether the amount of any input could have been reduced while producing the treatments' output bundle and using no more of any of the other inputs than what was observed. Again, the assumed set of technically feasible output/input configurations is assumed to be a convex combination of the observed experimental treatment data. This nonparametric efficiency test is a directional test of technical efficiency with respect to a specific input in a multiple input use context. The mathematical formulation is identical to (1)-(5) but with equation (2) replaced by:

$$\sum_{i=1}^{I} x_{\tilde{j}i}\lambda_i \leq x_{\tilde{j}0}(1-\tau) \qquad \text{for one specific input } \tilde{j}, \tag{6}$$

where $\tilde{j}$ is the specific input whose efficiency of use in the production system is being tested. With the new constraint, τ scales down the input of the specific input whose efficiency is being tested. The optimal objective value when this test is applied will be zero for an efficient treatment and strictly greater than 0 for an inefficient treatment. A value of 0.1, for example, indicates that the treatment could have used 10% less of input $\tilde{j}$ than was used for the treatment, while using no more than the treatment level of the other inputs and producing at least as much as the treatment level of each of the outputs.

The third test uses a profit (return above variable cost) maximization objective with both multiple outputs and inputs to identify the optimal treatment for given (observed) prices for inputs and outputs. All outputs and inputs are treated as variable in this analysis. The linear program for this test is:

$$\text{maximize} \qquad \sum_{k=1}^{K} p_k u_k - \sum_{j=1}^{J} w_j x_j \tag{7}$$

$$\text{subject to:} \qquad \sum_{i=1}^{I} u_{ik} \lambda_i \geq u_k \qquad \text{for every output } k, \tag{8}$$

$$\sum_{i=1}^{I} x_{ji} \lambda_i \leq x_j \quad \text{for every input } j, \text{ and} \tag{9}$$

$$\sum_{i=1}^{I} \lambda_i = 1, \; \lambda_i \geq 0, \tag{10}$$

where p_k is the price for output *k*, w_j is the price for input j, x_j is the variable level of input j, and u_k is the variable level of output *k* in the convex combination. Here, because the prices do not vary across treatments, there is only a single problem to be solved to determine the profit maximizing treatment(s), as well as the level of profit.[7]

In addition to these non-parametric tests for efficiency, linear programming sensitivity analysis was applied to determine the ranges of input and output prices for the problem defined by (7)-(10) for which the identified treatment remains optimal. This is a measure of the robustness of the optimality of the identified best treatment. These impacts are assessed using standard linear programming sensitivity analysis. Thus, the results indicate how far the price of each input or output can be changed before the optimal treatment choice changes, holding the prices of all other inputs and outputs constant.

3. Results

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[7] There will only be multiple optimal treatments if this linear program has multiple optimal solutions, and the optimal level of profit for each of these will be equal.

Each treatment is defined by the levels of two inputs, fish stocking density and feeding rate, plus a third input – time, which represents the harvest day. Since there are four levels for each input in the experimental design, and there are ten potential harvest days for the output measurements, a total of 160 treatments are compared. The treatments are numbered from 1 to 160 and a table with the complete list of the treatments and their associated identification numbers is present in Appendix B - Table 1. In the results tables presented here, the harvest day, the stocking density and the feed rate levels are also displayed to facilitate comparison and interpretation. Total feed input (kg/year), total fingerlings input (#/year), lettuce production (kg/year) and fish production (kg/year) are also expressed on an annual basis in the results, because variation in the number of days until harvest days will result in a different number of production cycles per year.

3.1. Test of output-oriented technical efficiency

For the fish output, 37 treatments were observed to be technically efficient as indicated by an asterisk in the fish production column in Table 2. Only treatments that are efficient according to at least one of the criteria (individual input or individual output) are listed in the table. The technically efficient treatments have feeding rates at or below what is recommended by the manufacturer. That is, very few technically efficient treatments had a feeding rate of +1.5% above the manufacturer's recommendation. The 28 treatments that are technically efficient in producing the lettuce output are also indicated in Table 2 (indicated by the asterisks in the lettuce production column). While days to harvest covered the full range from 21 to 30, the most frequently efficient joint production period was 30 with 10 instances of efficient production of both fish and lettuce. Production periods of 21 and 26 days were the next most frequent output efficient treatments, with six instances of efficient production of both outputs for both production periods. It is observed that all the treatments that were technically efficient in producing lettuce were also technically efficient in producing fish, but that the reverse was not true. All of the treatments that were efficient for fish production but inefficient for lettuce production had initial fingerling stocking density at the lowest level – 100 fingerlings/m^3 (see Table 2, columns 3, 7 and 8). ***[Place Table 2 near here]***

3.2. Test of input-oriented technical efficiency

Table 2 also indicates treatments with technical input efficiency. For the fish feed input, 37 treatments were observed to be technically efficient (see asterisks in the total feed column). The majority of the treatments exhibiting efficiency of feed use have feed levels below the manufacturer's recommended feeding rate with 14 treatments at 3.0% below the recommended rate and 9 treatments at 1.5% below the recommendation. Twelve treatments were at the recommended rate, and only 3 efficient treatments for feed use were at 1.5% above the recommended rate. During the experiment, treatments with the high feeding rate (+1.5%) often showed feed waste floating on the water in the fish tanks. Thus, it is not surprising that other treatments with lower feeding rates are more efficient. While efficient in terms of feed use, many of the treatments at feeding levels below the manufacturer's recommended rate of feed use are inefficient for lettuce production.

Table 2 also indicates that all 38 treatments that are technically efficient in using either input or producing either output are also technically efficient in using fingerlings (column 6). The lowest level of density (100 fish/m^3) was most frequent among the treatments found to be efficient in use of the fingerling input, at 18 out of 38 undominated techniques. Densities of 150 and 200 had frequencies of 6 and 5 out of 38, respectively, and the density of 250 had a frequency of 9 out of 38. For treatments found to be efficient in use of the fingerling input, the lowest density, the level of feed use tended to be low. That is, at a density of 100 fish/m^3 10 of the 18 treatments use a feeding rate of -3% relative to recommendations, 5 of 18 use a rate of -1.5%, 2 of 18 used the recommended feeding rate, and only one used the higher rate of 1.5% above the recommendation. In contrast, at the highest level of fish density, the feeding level of -3.0% was never associated with an efficient use of the fingerling input. This suggests that efficient use of the fingerling input must be coupled with adjustments to the feeding rate, with lower densities, not surprisingly, associated with lower feeding rates.

One treatment (#146) was efficient at using the fingerling input, but was not efficient at producing either output or at using the feed input. This is explained by the observation that the level of the feed input use is at a minimum over all observations for treatment 146, otherwise treatment 146 is dominated by treatment 160. While the use of fingerlings for treatments 146 and 160 is equal, treatment 160 uses less of the other input and produces more of each of the outputs than treatment 146. The question answered by the test is “could a convex combination of treatment input/output vectors have resulted in lower use of the fingerling input while producing at least as much of each output and using no more of the feed input?” Because 447.4 fingerlings/year is the minimum across observations, no convex combination of treatments can achieve a lower level of use of the fingerling input. This underscores the limitations of directional efficiency measures at the extreme boundaries of the data.

3.3. Identifying the profit-maximizing (return above cost of variable inputs) treatment

To identify the profit-maximizing treatment, all outputs and inputs are treated as variables and input prices are set to the levels paid at 0.18 R$/unit of tilapia fingerlings and 2.80 R$/kg for fish feed. To value output, the average observed regional market price of 20 R$/kg for juvenile tilapia and 1.57 R$/kg for lettuce were used.

The most profitable treatment at market average base prices is treatment #94 (harvest day 26, stocking density 250 fish/m^3 and feeding at the manufacturer recommended rate). The higher initial stocking density of fingerlings is advantageous for profit because it produces more juvenile fish, given sufficient nutrition, and thus increases revenue. In addition, the recommended feeding rate is preferred, because it is sufficient to support fish growth while limiting feed waste. Harvesting on the 26th day of the experiment is preferred because at this point, many lettuce units reach a good size, but the quantity of fish feed is low compared with harvesting in following days.

The objective coefficient (price) sensitivity analysis of the choice of optimal treatment to prices of inputs and outputs reveals several things (see Table 3). First, the optimality of the base treatment (#94) is generally robust with respect to output prices. The price of juvenile fish must be reduced by a factor of more than four in order to get a change in the optimal treatment. Increases in the price of juvenile fish have no impact until it becomes unreasonably high – nearly 75 times the base price. For the lettuce price, an increase of nearly 60 times the base price is required to cause a switch to another treatment, and the price of lettuce can decrease to zero without affecting the optimal treatment choice.

The optimality of the base treatment is likewise robust with respect to input prices. The increase in the price of fingerlings needed to induce a change in optimal treatment is quite large – a factor of five. The choice of treatment is similarly insensitive to the price of feed with the increase needed to induce a change in the optimal treatment being over a factor of four. For both fingerling and feed inputs, prices can decrease to zero without impacting the optimal treatment. It is interesting that the treatment that is more profitable when the feed price increases just enough to make treatment #94 non-optimal, shifts to treatment #78 (the same as treatment #94, but harvesting one day earlier). This implies that, prices must individually be changed quite substantially to change the optimal configuration of inputs from the levels in treatment #94. Table 3 displays the full range of sensitivity analysis and optimal treatments for input and output prices. However, our discussion focuses on the base and changes we deem to be within reasonable ranges. ***[Place Table 3 near here]***

4. Discussion

An experimental study of the productivity of an aquaponics system was conducted in Brazil between June and July of 2019. Four different levels of initial fingerling stocking density and four feeding rates relative to the manufacturer's recommendations were measured in a 30-day experiment. Inputs were measured throughout the 30-day production period, and outputs were measured or estimated during the last 10 days of experiment. The fish were grown to the juvenile stage. These juveniles, or large fingerlings, have good market potential as inputs to a commercial fish grow-out operation and can be harvested within the 30-day production period (Pinho et al. 2020). There is a good market for juveniles because it is economically advantageous for fish farmers to use juveniles rather than small fingerlings in order to "optimize the production and reduce the initial losses in grow-out due to predation in ponds and reservoirs" (Lima, Bergamin and Moro 2013). Cavero, Rubim and Pereira (2009) has shown the economic advantages of producing grow-out fish from larger juveniles.

A series of non-parametric efficiency tests was performed to determine which treatments had the potential to be technically efficient. The test employed for technical output efficiency is weak in the sense that, by testing for each output one at a time, while limiting all inputs to no more than what was used by that treatment and requiring at least as much of the other output is produced, a large number of treatments will be deemed efficient. For the 37 treatments of fish output that were found to be technically efficient, the best results presented feeding rates at or below the rate recommended by the manufacturer. In addition, the most frequently efficient joint production period was 30 days with 10 instances of efficient production of both fish and lettuce. It suggests that the aquaponic system provided adequate water quality, giving fish better use of nutrients in the diet and, simultaneously, providing adequate absorbable nutrients to the plants (Endut, Jusoh and Ali 2014). Treatments with early harvest are also found to be less efficient, in general, than treatments that allow more time for output growth. Thus, it appears that it is important to provide the fish and plants adequate time to grow.

However, in a 50-day aquaponics experiment, Zou et al. (2016) found low feed conversion ratios, and the authors associate this result with the low protein content (CP 23%) of the feed provided to the fish. In the present study fish-plant production was found to be efficient despite the shorter cultivation time compared to the previous study. We speculate that this is probably due to the improved protein content (CP 36%) of the feed provided to the fish. It is important to highlight that nitrogen is the most important nutrient for both fish and plants and, in aquaponics, the only nitrogen source is fish feed (Endut, Jusoh and Ali 2014). According to Cyrino et al. (2010), overfeeding or the use of unbalanced feeds reduces nutrient uptake by fish, which can result in excess organic matter in production system. The excess organic matter reduces water transparency and changes water quality, especially by reducing the dissolved oxygen concentration at night, inducing respiratory and biochemical stress with serious health risks to fish and possible losses in the production system. Therefore, it is important to balance fish stocking density with feed supply, so the organic compounds can be successfully used by plants, and maintain the system's water quality.

A nonparametric analysis of technical efficiency using linear programming techniques was used by Llewelyn and Williams (1996) for irrigated farms in the west-central part of East Java, Indonesia. The authors found farmers in general are efficient relative to each other, but those found to be inefficient appear to be explained by scale inefficiencies rather than technical inefficiencies. In addition, inefficient farms used excessive levels of inputs, particularly nitrogen fertilizer. In a similar approach, applying standard linear programming-based nonparametric efficiency tests, Preckel, Akridge and Boland (1997) assessed the economic rationality of the behavior by fertilizer retailers – that is, these tests are applied at the individual firm level. They found that the fertilizer retailers in their dataset acted as variable cost minimizers, but not as revenue and profit maximizers. This result shows the importance of testing efficiency from a variety of perspectives.

Stocking density of fish is a key factor for balancing the aquaponic ecosystem (Birolo et al. 2020). Among the treatments that were efficient in using the fingerling input at the lowest density of 100 fish/m^3, more than half were inefficient at producing the lettuce output. At higher stocking densities, all treatments that were efficient with respect to any input or output were efficient at producing lettuce. This confirms that, at the lower level of fish stocking density, the effluent in the water is insufficient to provide adequate nutrients to the plants. With more fingerlings in the tank, there will be more nutrients for the plants and more final fish production. Hundley (2013) tested different levels of fish stocking density for basil-tilapia aquaponics production finding that an initial high density level of 500 g/m^3 result in better basil growth relative to lower densities. Nhan et al. (2019) looked for an optimum stocking density of swamp eel in an aquaponic system integrated with watercress that allows minimum water exchange, reduce water pollution and obtain good growth for both fish and plant. The authors found that higher stocking density of fish yielded relatively high production as well as high accumulation rate of nutrients in the system. They also indicated that aquaponics is the only alternative to increase swamp eel's aquaculture, without destroying the environment.

Bosma et al. (2017) reported that a good strategy for success in an aquaponics activity is to start with catfish, and after mastering the system's management, change to a more expensive species such as tilapia for specific markets. Evaluating aquaponics economic viability, Kodama (2015) conducted an experiment in the Cerrado region in Brazil and used Monte Carlo sampling to simulate the yield variation in a model of the production system incorporating risk. The author found that aquaponics is economically viable and that labor is the main cost item. A comparison between aquaponics and hydroponics was also studied in Brazil by Carvalho et al. (2017). The results presented in that study show that both systems fit well within the South region using tilapia and lettuce and that high yields combined with low costs allow profitable investment in both activities even to small farmers. In our work, observed average market prices for inputs and outputs were used to determine which input treatment and resulting outputs yielded the highest profit. Linear programming sensitivity analysis was then used to assess the ranges for input and output prices over which the optimal choice of technology is robust. This sensitivity analysis yields insight into which prices are most important for determining the production technology that maximizes revenues net of variable costs.

Nonparametric efficiency measurement is shown to be a useful tool for screening experimental data to identify promising production management strategies (Li et al. 2016). No previous research has applied nonparametric efficiency tests to aquaponics production in Brazil, and we are not aware of research using these tests on experimental data to determine the set of undominated strategies. Several studies focused on other production systems have used this type of analysis, but these have generally focused on assessing the technical or allocative efficiency of alternative technologies, with the latter focused on assessing the economic behavior of agents. An example that focuses on aquaculture is due to Long et al. (2020), which assessed technical efficiency of Vietnamese white shrimp farming households. These past studies are ex post analyses where the researcher is asking if the producing unit could have been more efficient. Here, we are concerned with identifying *a priori* based on experimental data, what technologies could be efficient in the absence of price information, as well as, for a given set of observed prices, which technology produces highest net returns and how robust that technology‘s optimality is to price variations.

Farrell (1957) argued that the productive efficiency of an industry is important to both the economic theorist and the economic policy maker. Using data from a U.S. industry, the author discussed the fundamental assumptions underlying nonparametric efficiency analysis, including issues of returns to scale and technical efficiency as well as allocative efficiency or the response of economic agents to market prices. In the same way, Charnes, Cooper and Rhodes (1978) evaluated decision-making units with common inputs and outputs through the development of measures of “decision making efficiency”. The authors concluded that there are a variety of ways to evaluate the efficiency of decisions in order to improve the control and planning of the activities. They focused on public programs as an area where, unlike private enterprises, input/output data should be available.

In our work, these data are obtained through experimental means, and hence data availability is a moot point.

Coelli (1995) observed that the econometric approach is parametric and subject to specification error, while the linear programming approach is nonparametric, but generally lacks the firm statistical basis that the econometric approach has, making statistical hypothesis testing more challenging. Simar and Wilson (2000) proposed methods for extending the linear approach to allow statistical inference, and these techniques are applied to aquaculture production systems in Vietnam by Long et al. (2020). While there is no perfect method of measuring efficiency, either the linear programming or econometric approaches present better measures of efficiency than only partial efficiency measures, like output per unit of land or labor. A comparison between parametric and nonparametric approaches was done by Sharma, Leung and Zaleski (1999) using a sample of swine producers in Hawaii. They found that both approaches presented inefficiencies, but the exclusion of outliers in the sample increased the technical efficiencies.

Using regional average prices, the optimal treatment (harvest on the 26th day, density of 250 fish/m^3 and feeding at the manufacturer recommended rate) is identified as the most profitable under current market conditions, i.e., with the highest return above variable costs. Linear programming objective coefficient sensitivity analysis of this treatment showed that this best treatment is sensitive to the relative prices of juvenile fish and lettuce output. This further demonstrates the usefulness of linear programming tools for not only screening experimental data and identifying the optimal strategy given market prices, but also for the assessment of the robustness of the identified strategy.

While the results of this research are encouraging, the conclusions have limitations. The experiment was conducted at a single site and under specific conditions like climate, selected plants and starting size of fingerlings. However, despite the limitations, our results provide valuable insights for government and private institutions working on aquaponics in Brazil. Aquaponics is an emerging enterprise, and having a means to identify promising joint production systems in terms of economic returns may increase the likelihood of success of the enterprise. The fact that aquaponics has environmental benefits, especially for dry regions, is an additional benefit that was not explicitly valued in the analysis.

5. Conclusion

The results from the analysis reveal important information for current and potential aquaponics farmers that may assist them to better assess options for investment in aquaponics relating to input use, cost and profits, and guidance in producing fish and vegetables in a more sustainable way. Although the experiment was conducted in Brazil, the methods can readily be adapted to other production environments as well as other types of production systems that are amenable to experimental assessment of production practices.

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Appendix A

Fig. 3 Photo of the greenhouse where the experiment was conducted before the start

Fig. 4 Photo of the greenhouse where the experiment was conducted with the lettuce at the initial stage

Fig. 5 Photo of the greenhouse where the experiment was conducted with the lettuce at the final stage

Appendix B

[Place Table 1 here]