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System Design and Co-Product Streams: Does Technological Choice Matter for Aquaponic Profitability?

Grace Gibbons and Tanner McCarty

Population growth, urbanization and climate change will create future challenges for agribusiness. One particularly vexing challenge will be producing more food using less land and water. Aquaponics offers the potential to overcome these obstacles, but a lack of research providing insight into managerial decision-making in this industry limits its effectiveness. This research is particularly lacking in the realm of aquaponic technological selection. This study compares the expected profitability of four leading aquaponics production systems. It compares expected net present value for coupled and decoupled aquaponic platforms, with and without a co-product capture for organic fertilizer. Technological choice has a considerable impact on aquaponic profitability. Expected net present value estimates ranged from $87,507 to $156,599 across the four technological combinations considered. Decoupled platforms combined with an organic fertilizer co-product capture provided the highest expected net present value. This result holds under a variety of economic conditions.

Key words: Aquaponics, Benefit Cost Analysis, Techno Economic Analysis, Benefit Cost Analysis

A combination of world population and income growth are expected to increase food demand by 50% in 2050 (Pinstrup-Andersen, 2018). This increase in food demand, combined with tightening input constraints for land and water, creates a complex problem for agricultural managers. How to produce more with less? Managers' abilities to solve this problem while remaining profitable, environmentally sustainable, and socially equitable influences both their firm's future viability and the standard of living worldwide. Aquaponics presents a potential solution to this problem.

Aquaponics production enables the production of both vegetables and fish in one controlled system. The hydroponically grown vegetables utilize and purify the wastewater from the aquaculture subsystem (Palm et al., 2018). This feature allows aquaponic operations to produce the same vegetable output as traditional field production, while requiring only 5-14% of the water and 9.5% of the land (Addy et al., 2017; Kiss et al., 2015; Pinstrup-Anderson, 2018; Van Ginkel, Igou, and Chen, 2017). Aquaponic systems also have efficient feed conversion ratios for protein production. Fish require less feed per kilogram of added growth than other animal-sourced foods such as

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Grace Gibbons is a Master's degree graduate student and Tanner McCarty is an assistant professor, both in the Department of Applied Economics at Utah State University, Logan. This research was supported by funding from the Utah Agricultural Experiment Station (project number UTAO 1443).

beef, mutton, and goat (Tilman and Clark, 2014). Aquaponic operations exploit these efficiencies by symbiotically raising fish and vegetables in a system that preserves water, conserves space, maximizes feed to food conversion, and reduces pollution.

In addition to enhancing technical efficiency, aquaponic products contain food attributes that resonate with a growing market demographic. Attributes such as locally, sustainably, and organically produced are desired by a growing segment of the market and can command a price premium (Hughes et al., 2017; Nemati and Saghain, 2018; Rankin et al., 2011; Tavella and Hjortso, 2012; Vega-Zamora et al., 2013). Fish and vegetables grown through aquaponics often contain these attributes. The ability to produce food on small sections of non-arable land near urban centers is another aquaponic benefit. This location flexibility could both lower food transport's energy footprint while allowing greater access of fresh produce within under-served food desserts.

Despite the aforementioned benefits, success of early entrants into the nascent aquaponic production U.S. market is mixed. Disparity in outcomes of entrants, such as Superior Fresh's continued expansion and Urban Organics bankruptcy, suggests management decisions for aquaponics operations matter. Plant managers make dozens of decisions on technological choices such as hydroponic production methods, system designs, and operation size. The problem is there is scant research comparing the economic viability across these different technologies. This leaves aquaponic managers without enough information to choose the optimal technological selection. We use Techno Economic Analysis (TEA) and comparative statistics to address this problem. We use production data from engineering literature and incorporate price data for the inputs/outputs associated with each technology. We focus our analysis on two key decisions influencing the profitability of an aquaponics operation: 1) the use of a coupled or decoupled production system; and 2) whether to capture discharged fish sludge to produce an organic fertilizer co-product. We estimate the profitability of these technologies under four different technological combinations. We address the following questions: a) Is the benefit of having higher tomato yields of the decoupled system worth the higher water cost? b) Is the additional revenue associated with processing fish sludge into organic fertilizer warranted after considering the increased cost?

Background

Previous Research

Fish and crops have been symbiotically produced for thousands of years (Goddek et al., 2015). It was not until 1977 that Ludwig Naegel created the first model of modern aquaponics in Germany. He raised tilapia in a recirculating aquaculture system while growing iceberg lettuce and tomatoes in the hydroponic subsystem (Palm et al., 2018). Since then, numerous studies have examined the engineering and chemistry behind aquaponics operations. However, only a few studies have quantified the economic factors behind them. The majority of these economic studies evaluated the profitability of one specific aquaponics operation at the University of the Virgin Islands (Bailey et al., 1997; Rakocy et al., 2011; Simonetti, 2015). Another study evaluated small-scale aquaponics in Hawaii finding that while aquaponics is profitable, its success is sensitive to output price (Tokunaga et al., 2015). Another study used an international survey to analyze the profitability, methods, and yields of 257 small operations. Less than one-third of the respondents in that study were profitable (Love et al., 2015). All previous economic studies lacked economic analysis governing technological selection.

A smaller strand of research has quantified management/technological decisions for aquaponic production. Quagrainie et al. (2018) compared the profitability of aquaponics to hydroponics. They found that aquaponics is more profitable if the crops are sold at an organic premium. They also compared aquaponics operations of three varying sizes and found aquaponics experiences economies of scale. Petrea et al. (2016) compared the deep-water culture hydroponic subsystem technique to the light expanded clay aggregate hydroponic subsystem technique and found that light expanded clay aggregate led to higher profitability. Bosma et al. (2017) quantified the impact fish and vegetable choice has on the profitability of aquaponics. Yet research comparing the economic viability of system design choices (the structure of the aquaponic system, holding all other subsystem techniques constant) and the inclusion of co-product streams is non-existent. This research fills the gap by conducting a TEA of four same-sized aquaponics operations. We compare two different prominent system designs with and without the option of implementing an organic fertilizer co-product capture to determine the most profitable technological combination.

Technological Explanation

The coupled system, also referred to as the closed-loop or balanced system, is the original aquaponics system design. It operates in a unidirectional flow of water. As shown in Figure 1, water runs from the fish rearing tanks through the nitrifying bacteria (biofilter), to the hydroponic troughs, and directly back to the fish rearing tanks.

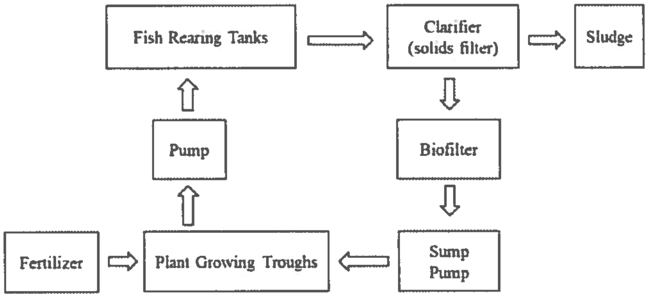

Figure 1. Coupled Aquaponic System Design.

A more recent system design is the decoupled or open-loop system. The decoupled system operates similar to the coupled system from the fish-rearing tanks to the hydroponic troughs for plant production. The key difference in this system, as shown in Figure 2, is that water is discharged or treated before fresh water is pumped into the fish-rearing tanks.

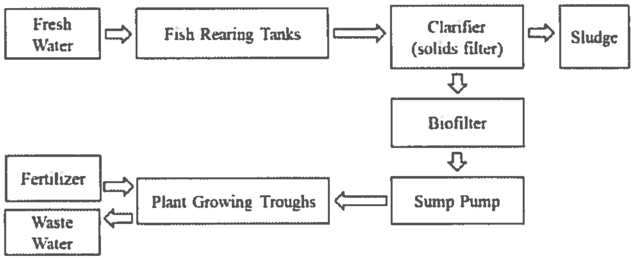

Figure 2. Simplified Decoupled Aquaponic System Design.

The decoupled system allows better control over water pH, temperature, and other nutrient levels compared to the coupled system. This leads to higher vegetable yields. The drawback to the decoupled technology is that it requires more water. This leads to a higher operating cost (Pattillo, 2017). An engineering study comparing input requirements and vegetable output across these two systems found decoupled systems achieve a 36% higher vegetable yield and comparable fish yields compared to coupled systems (Monsees, Kloas, and Wuertz, 2017). This same study also found decoupled systems require approximately 2.6 times the water. Management decisions require understanding this tradeoff's effect on a project's net present value (NPV) and, thus, is a key part of our analysis.

Aquaponic margins on fish and vegetables are small. Thus managers could consider additional revenue streams. The implementation of co-product streams enhances profitability in other agricultural industries. Corn ethanol plants rely on co-product revenue from dried distillers' grains to maintain profitability. Wineries follow the same strategy by using leftover skins, seeds, and stems to make grappa. All aquaponics systems use a clarifier tank to collect the fish waste too large for the plants to absorb. Typically, this sludge is treated and discharged when the clarifier tank gets cleaned. This sludge could be collected and dried to sell as organic fertilizer. While the profitability of fertilizer capture has not been explored within the aquaponic literature, the technology has been adopted by the commercial aquaculture plant Fishcat Farms (Dodd, 2013). This process yields additional revenue, but also requires additional costs. Without measuring these effects, it is not obvious which is greater. The implications an organic fertilizer co-product stream could have on NPV makes it a key component of our analysis.

Methods

Model

We compare the economic viability of four different technological combinations (the coupled system against the decoupled system with and without a co-product stream) using Techno-Economic Analysis. TEA is a framework that combines economic and engineering data to measure the economic attractiveness of alternative technological options. This article pulls existing data for aquaponic machinery and input requirements, plant and fish outputs, and best management practices from the engineering literature for each technology. It then adds price data for the inputs/outputs associated with the given technology. The economic desirability of each technology is then recovered by calculating the NPV of each technology by weighing the disparate future costs and benefits over the life of each project. Equation 1 explains the NPV calculation where T denotes the life of the project, t represents the number of years in the future where costs and benefits occur, and δ denotes the discount rate. B_t represents total benefits in a given year and C_t represents total costs for that year.

$$NPV = \sum_{t=0}^{T} \frac{B_t}{(1+\delta)^t} - \sum_{t=0}^{T} \frac{C_t}{(1+\delta)^t} \quad (1)$$

After conducting a TEA for the four technology combinations under baseline assumptions, we calculate the NPV for all combinations under varying assumptions to test the validity of the results in different economic situations. To check the robustness of our results, we use comparative statics analysis. Comparative statistics is useful to evaluate how results, in this case NPV, changes in response to exogenous parameters such as price received or input cost. This is of particular interest to aquaponics because the price of locally grown organic vegetables, price of locally raised fish, the cost of water, the cost of labor, and the manager's discount rate all vary across time and location.

Data and variables

To compare the economic viability of coupled and decoupled systems, we required a study that tested them both at the same scale. A previous study, henceforth referred to as study #1, compared the scientific parameters of a closed loop and an open loop prototype system performed in Berlin, Germany (Monsees, Kloas, and Wuertz, 2017). Study #1 used the same-sized fish-rearing tanks and hydroponic grow areas for both technologies to determine input requirements and outputs for each system. The aquaculture units of both systems were intermediate-commercial size with 240 ft^3 of fish-rearing area while the hydroponic units were pilot size, growing 15 tomato plants each.

To compare the profitability of both technologies at an intermediate-commercial size, the hydroponic units needed to be scaled up to a size that matched the aquaculture unit. There was a second study that examined an optimized decoupled aquaponics system at the intermediate-commercial size in the same facility, henceforth referred to as study #2 (Kloas et al., 2015). The goal of study #2 was to operate a decoupled aquaponic system where the ratio of fish to plants provided favorable plant growing conditions. Since the difference in coupled and decoupled systems occurs after hydroponic plant production, we assumed that an optimized coupled system would have a similar-sized hydroponic growing area as an optimized decoupled system. We used this information to modify the original plant growth area parameters of study #1 to match the plant growing area demonstrated by study #2 for both systems. Overlaying the parameters of the optimized decoupled hydroponic subsystem from study #2 was the pilot size hydroponic subsystem of study #1 created the means for which the coupled and decoupled systems could be consistently compared at the intermediate-commercial level. We then retrieved prices for each piece of equipment and inputs required for each system to estimate costs. Tables 1 and 2 show the parameters used in the TEA for the coupled and decoupled systems, respectively. We applied local estimations of water and electricity costs from rates in Park City, Utah. We chose Park City because its relatively dry climate makes water-conserving technology more interesting and its high per capita income would increase consumer willingness to pay for local, organic, sustainable produce.

To be consistent between studies #1 and #2, we asumed an aquaponic production system of tomato and tilapia. Tomato price data came from the Utah State University Extension on Utah Farmers Market and Grocery Store Pricing data from 2016-17 (USU Extension, 2017). In 2019 dollars, organic slicing vine tomatoes had an average price of \$2.67 and a yearly standard deviation of \$0.56.[1] We used this mean and standard deviation to model a normal price distribution with @RISK software. TEA draws from within this normal distribution to provide stochastic NPV values depending on fluctuating tomato prices. By creating stochastic pricing, we quantify the risk of prices going up or down. Tilapia price data came from the U.S. Department of Agriculture's (USDA) Quick Stats (USDA National Agricultural Statistics Service (NASS), 2018). Although there was no time series of data, the 2018 national average and standard deviation for the price received for food-size tilapia provided the most recent data available.[2] The average tilapia price of \$2.68 and standard deviation of \$1.32 were used (USDA NASS, 2018).

Each system holds 363 tomato plants on a six-month cycle, 726 tomato plants a year (Kloas et al., 2015). A tomato plant in the coupled system produces 13.45 lbs. of tomatoes while a plant in the decoupled system produced 18.08 lbs. (Monsees, Kloas, and Wuertz, 2017). We estimated yearly output in the coupled system at 9,762 lbs. of tomatoes, while the decoupled system was 13,124 lbs. The improved pH and temperature control in the decoupled system increases tomato productivity (Monsees, Kloas, and Wuertz, 2017). The yearly output of tilapia was 1,964 fish per year of approximately 1.5 lbs., an expected 2,946 pounds of tilapia for both systems.

The primary cost difference between coupled and decoupled systems comes from differences in water requirements. Water usage rates for each system were determined in two parts: 1) the initial water needed to fill the system; and 2) the yearly water usage. Study #2 provides an estimated water requirement for a decoupled system. The intermediate commercial-scale decoupled system showed a 3.83% daily water usage in a 3,434 -gallon system, or 48,008 gallons per year. We estimated the water requirement for the coupled system by taking the water requirement for a commercial decoupled system in study #2 times the ratio of water requirements between coupled and decoupled pilot

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[1] These tomatoes did not have a sustainability certification and serve as a conservative price range.

[2] Average price of all tilapia sold. This price range is conservative for a locally and sustainably produced fish.

systems in study #1. In the pilot study, the coupled system used 507 gallons while the decoupled system used 1,311 gallons (Monsees, Kloas, and Wuertz, 2017). This means a coupled system consumes 38.7% of the water that a decoupled system consumes, or 18,579 gallons per year.

Collecting and drying the fish waste requires constructing a box to dehydrate the sludge. This requires four planks of wood to hold a tarp. The water is dumped into the tarp and dries from one to four weeks. Tables 3 and 4 show the cost and benefit of adding on a fertilizer capture system for coupled and decoupled systems, respectively. We assumed local weather conditions representative of Park City, Utah, to estimate evaporation rates and months where fertilizer capture is feasible. Fertilizer capture only works in months when water evaporates. Evaporation rates used in this research correspond to Provo, Utah, since it is the closest geographical data point to Park City. The data suggested eight months of evaporation occurs in the area (Western Regional Climate Center, 2005). In March, 2.59 inches evaporate. The wastewater from the first week of March would not fully evaporate until the first week of April. As summer approaches, it takes less time for the water to evaporate. In order to accommodate the month of March, five boxes need to be constructed. After that, the five boxes would not be needed until September and October, when evaporation rates slow down again. This makes for 31 weeks of waste collection. The boxes would fill up 3.32 inches with the 1,500L of water. The percent of dry weight of the wastewater at this point is 0.2% for the decoupled system, and 0.18% for the coupled system (Monsees, Kloas, and Wuertz, 2017). In order to achieve the required 35% dry weight, the volume would decrease to 8.57L for the decoupled system and 7.71L for the coupled. Once the fertilizer reaches the desired dry weight percentage, it is weighed, packed into bags, and sold. Over a year, this captures 586 lbs. of fertilizer ($1,172) for the decoupled system and 527 lbs. of fertilizer ($1,054) for the coupled system.

Table 1. Coupled System Parameters.

Item	Details	Quantity	Price	Total Cost	Source
Fixed Costs Coupled Aquaponic System					
Fish tank	1.7m^3	4	$563.44	$2,253.74	(Tank and Barrel, 2019b)
Aerator/blower	20 W	1	$107.96	$107.96	(Amazon, 2019)
Biofilter tank	2m^3	1	$1,166.36	$1,166.36	(Tank and Barrel, 2019a)
Biofilter media	1605 m^2	1	$45.00	$45.00	(Algae Barn, 2019)
Clarifier	1.9 m^3	1	$1,166.36	$1,166.36	(Tank and Barrel , 2019a)
Plumb piping		1	$449.19	$449.19	(Bailey et al., 1997)
Pump	10L/min	1	$216.83	$216.83	(Cole Palmer, 2019)
Sump tank	200 gal	1	$502.60	$502.60	(Bailey et al., 1997)
Heating system	10L/20,000W	1	$1,920.00	$1,920.00	(Aquaponic Source, 2019)
Water quality kit	-	1	$319.28	$319.28	(Simonetti, 2015)
Back-up power system	12 V	1	$268.00	$268.00	(Endless Food Sys, 2019)
Lighting timer	1725 W	1	$20.59	$20.59	(Hydro Farm, 2019)
Sodium discharge lLamps	600W	54	$42.85	$2,313.63	(Growers House, 2019)
NFT system	363 plant capacity	1	$2,999.00	$2,999.00	(Greenhouse Megastore, 2019)
Greenhouse structure	ft^2	1,000	$32.23	$32,225.67	(Robbins, 1999)
Temp control installation	ft^2	1,000	$3.30	$3,299.30	(Robbins, 1999)
Water to fill system[a]	Kilo-gallons	3.434	$8.85	$30.39	(Park City, 2019)
Water hookup cost[a]	3/4" meter	1	$801.94	$801.94	(Park City, 2019)
Yearly Operating Costs Coupled System					
Fish feed Aller-Aqua	lbs	1,701	$0.91	$1,543.40	(Ruvu Fish Farm, 2019)
Tilapia fingerlings	fingerling	1,964	$0.56	$1,099.84	(FAO, 2019)
pH adjustors ($CaCO3$)	lbs	165.1	$0.20	$33.02	(FeedX, 2019)
Tomatoes	726 seeds	726	$170.40	$170.40	(Johnny's Seeds, 2019)
Rock wool cubes	10*10*4.3 cm	726	$0.60	$435.60	(Floraflex, 2019)
Fertilizer Krista K plus	lbs	74	$1.89	$139.96	(M.B. Ferts, 2019)
Fertilizer CalciNit	lbs	28.82	$1.35	$38.97	(M.B. Ferts, 2019)
Fertilizer Manna Lin M	gallons	2.24	$26.44	$59.15	(Hauert Manna, 2019)
Fertilizer $KHCO_3$	lbs	32	$4.25	$136.00	(Ingredi, 2019)
Variable water cost[a]	kilo-gallons	18.58	$8.85	$164.40	(Park City, 2019)
Base monthly water fee	3/4" meter fee	12	$65.52	$786.24	(Park City, 2019)
Electricity - aerator 200W	kWh	1,752	$0.08	$141.21	(Electricity Local, 2019)
Natural gas - water heater	ft^3	312.15	$4.31	$1,345.36	(Natural Gas Local, 2019)
Electricity - 54 SDL's 600W	kWh	70,956	$0.08	$5,719.05	(Electricity Local, 2019)
Electricity - greenhouse	kWh	10,000	$0.08	$806.00	(Electricity Local, 2019)
Electricity - timer 1725W	kWh	5,037	$0.08	$405.98	(Electricity Local, 2019)
Depreciation	straight line	1	$3,154	$3,154	Author Calculations
Yearly Coupled Revenue					
Tomatoes	lbs	9,762	Mean:$2.67 SD: $0.56	$26,064.54	(USU Extension, 2017)
Tilapia	lbs	2,946	Mean:$2.68 SD: $1.315	$7,895.28	(USDA NASS, 2018)

[a] Park City, Utah.

Table 2. Decoupled System Parameters.

Item	Details	Quantity	Price	Total Cost	Source
Fixed Costs Decoupled Aquaponic System					
Fish tank	$1.7m^3$	4	$563.44	$2,253.74	(Tank and Barrel, 2019b)
Aerator/blower	20 W	1	$107.96	$107.96	(Amazon, 2019)
Biofilter tank	$2m^3$	1	$1,166.36	$1,166.36	(Tank and Barrel, 2019a)
Biofilter media	$1605\ m^2$	1	$45.00	$45.00	(Algae Barn, 2019)
Clarifier	$1.9\ m^3$	1	$1,166.36	$1,166.36	(Tank and Barrel, 2019a)
Plumb piping		1	$449.19	$449.19	(Bailey et al., 1997)
Pump	10L/min	1	$216.83	$216.83	(Cole Palmer, 2019)
Sump tank	200 gal	1	$502.60	$502.60	(Bailey et al., 1997)
Heating system	10L/20,000W	1	$1,920.00	$1,920.00	(Aquaponic Source, 2019)
Water quality kit		1	$319.28	$319.28	(Simonetti, 2015)
Back-up power system	12 V	1	$268.00	$268.00	(Endless Food Sys, 2019)
Lighting timer	1725 W	1	$20.59	$20.59	(Hydro Farm, 2019)
Sodium discharge lamps	600W	54	$42.85	$2,313.63	(Growers House, 2019)
NFT system	363 plant capacity	1	$2,999.00	$2,999.00	(Greenhouse Megastore, 2019)
Greenhouse structure	ft^2	1,000	$32.23	$32,225.67	(Robbins, 1999)
Temp control installation	ft^2	1,000	$3.30	$3,299.30	(Robbins, 1999)
Water to fill system[b]	kilo-gallons	3.434	$8.85	$30.39	(Park City, 2019)
Water hookup cost[b]	3/4" meter	1	$801.94	$801.94	(Park City, 2019)
Yearly Operating Costs Coupled System					
Fish feed Aller-Aqua	lbs	1,701	$0.91	$1,543.40	(Ruvu Fish Farm, 2019)
Tilapia fingerlings	fingerling	1,964	$0.56	$1,099.84	(FAO, 2019)
pH adjustors ($CaCO_3$)	lbs	161.9	$0.20	$32.38	(FeedX, 2019)
Tomatoes	726 seeds	726	$170.40	$170.40	(Johnny's Seeds, 2019)
Rock wool cCubes	10*10*4.3 cm	726	$0.60	$435.60	(Floraflex, 2019)
Fertilizer Krista K plus	lbs	74	$1.89	$139.96	(M.B. Ferts, 2019)
Fertilizer CalciNit	lbs	28.82	$1.35	$38.97	(M.B. Ferts, 2019)
Fertilizer Manna Lin M	gallons	2.24	$26.44	$59.15	(Hauert Manna, 2019)
Fertilizer KHCO3	lbs	32	$4.25	$136.00	(Ingredi, 2019)
Variable water cost[b]	kilo-gallons	48	$8.85	$424.80	(Park City, 2019)
Base monthly water fee	3/4" meter fee	12	$65.52	$786.24	(Park City, 2019)
Electricity - aerator 200W	kWh	1,752	$0.08	$141.21	(Electricity Local, 2019)
Natural Gas - water heater	ft^3	312.148	$4.31	$1,345.36	(Natural Gas Local, 2019)
Electricity - 54 SDL's 600W	kWh	70,956	$0.08	$5,719.05	(Electricity Local, 2019)
Electricity - greenhouse	kWh	10,000	$0.08	$806.00	(Electricity Local, 2019)
Electricity - timer 1725W	kWh	5,037	$0.08	$405.98	(Electricity Local, 2019)
Depreciation	straight line	1	$3,154.59	$3,154.59	Author Calculations
Yearly Decoupled Revenue					
Tomatoes	lbs	13,124	Mean: $2.67 SD: $0.56	$35,041.08	(USU Extension, 2017)
Tilapia	lbs	2,946	Mean: $2.68 SD: $1.315	$7,895.28	(USDA NASS, 2018)

[b] Park City, Utah.

Table 3. Fertilizer Capture Added to Coupled System Parameters.

Item	Details	Quantity	Price	Total Cost	Source
Fixed Costs Fertilizer Capture Added to Coupled System					
Wood planks	2in x 8in x 12ft	10	$8.33	$83.30	(Lowe's, 2020a)
Wood planks	2in x 8in x16ft	10	$11.61	$116.10	(Lowe's, 2020b)
Tarps	15ft 2in x 19ft 6in	5	$34.99	$174.95	(Harbor Freight, 2020)
Labor	1 hour/box	5	$20.00	$100.00	Author Calculations
Scales		1	$69.00	$69.00	(U-Line, 2020a)
Yearly Operating Costs Fertilizer Capture Added to Coupled System					
Bags	2 lb. bags	263	$0.15	$39.45	(Alibaba, 2020)
Ties	6" ties	263	$0.01	$1.58	(U-Line, 2020b)
Labor	labor hours	69	$8.50	$589.00	Author Calculations
Yearly Revenue for Fertilizer Co-Product Added to the Coupled System					
Fertilizer	Bags	263	$4.00	$1,052.00	(Fishnure, 2020)

Table 4. Fertilizer Capture Added to Decoupled System Parameters.

Item	Details	Quantity	Price	Total Cost	Source
Fixed Costs Fertilizer Capture Added to Decoupled System					
Wood planks	2inx8inx12ft	10	$8.33	$83.30	(Lowe's, 2020a)
Wood planks	2in x 8in x16ft	10	$11.61	$116.10	(Lowe's, 2020b)
Tarps	15ft 2in x 19ft 6in	5	$34.99	$174.95	(Harbor Freight, 2020)
Labor	1 hour/box	5	$20.00	$100.00	Author Calculations
Scales		1	$69.00	$69.00	(U-Line, 2020a)
Yearly Operating Costs Fertilizer Capture Added to Decoupled System					
Bags	2 lb. bags	293	$0.15	$43.95	(Alibaba, 2020)
Ties	6" ties	293	$0.01	$1.76	(U-Line, 2020b)
Labor	labor hours	69	$8.50	$589.00	Author Calculations
Yearly Revenue for Fertilizer Co-Product Added to the Decoupled System					
Fertilizer	Bags	293	$4.00	$1,172.00	(Fishnure, 2020)

Results

Techno-Economic Comparison of 4 Available Technology Combinations

This article set out to answer two key questions: 1) Is the benefit of having higher tomato yields of the decoupled system worth the higher water cost?; and 2) Is the additional revenue associated with processing fish sludge into organic fertilizer warranted after considering the increased cost in storage, labor hours, and fertilizer bags? Figure 3 displays the results to both questions. It shows the expected NPV and associated cumulative distribution function (CDF) of all four technology combinations.

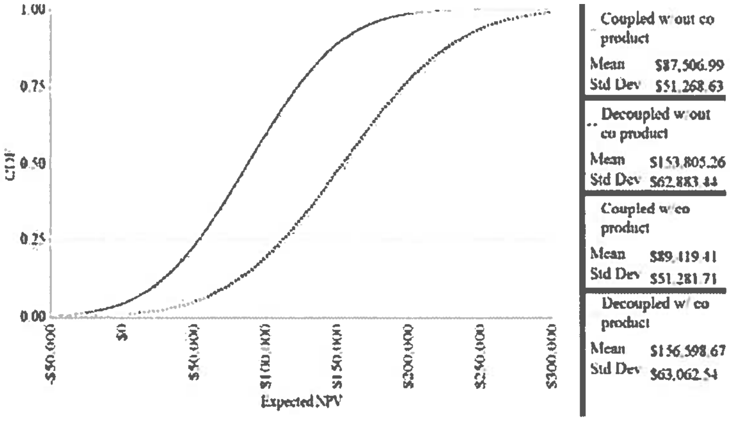

Figure 3. CDF for NPV Associated with each Technological Combination.

The TEA suggests the highest expected NPV occurs for the decoupled system with fertilizer capture at $153,805. Decoupled systems are preferred over coupled in all combinations. They become even more profitable with fertilizer capture. These differences matter. The most profitable technology combination, decoupled with fertilizer capture, yields an expected NPV that is $69,092 (79%) higher than the least profitable technology combination, coupled without fertilizer capture. Decoupled systems with fertilizer capture also contain the lowest probability of negative returns at 0.7%. We attribute the superior performance of decoupled systems to the relative importance of increased tomato yields against increased water cost. The increase in the present value of revenue associated with a switch from coupled to decoupled is $68,276. Present value of cost only increases by $1,981 when switching from a coupled to decoupled system. Higher water use drives this increase in cost. Park City has three categories of water pricing: fixed, base, and variable. The fixed cost of connecting a pipe to a business and the monthly base rate is the same for both systems. Only the variable cost of water differed. The decoupled system requires 4 kilo-gallons of water per month as opposed to the coupled systems that requires 1.55 kilo-gallons of water per month. The variable cost of water is only $8.85 per kilo-gallon. The variable cost of water had to increase to $192 per kilo-gallon to make a manager indifferent between a coupled and decoupled system.

Fertilizer capture marginally benefitted both systems, especially in the decoupled system which releases slightly more sludge (Monsees, Kloas, and Wuertz, 2017). Implementing fertilizer capture increased the NPV of the decoupled system by $2,797 and the coupled by $1,915. Fertilizer capture is cheap to implement and operate, but produces limited output. Both systems efficiently convert fish waste to biomass and can only operate fertilizer capture for eight months. The coupled system produced 526 pounds of organic fertilizer per year and the decoupled produced 586 pounds. This technology would be more attractive in a larger operation or in a region with higher evaporation rates.

Comparative Static Analysis of Key Parameters

Table 5 displays the impact on NPV from a shift of tomato prices by one standard deviation above and below the mean across the four technological combinations. The organic tomato price has a large impact on expected NPV across all technological combinations. Aquaponics managers should carefully consider the local market in which they plan to locate. Local markets that have a high willingness to pay for organic/local/sustainable/fresh produce will be more attractive. The marketing channel an aquaponic manager decides to sell through could also be important. For instance, selling a "premium" product to upscale restaurants could achieve higher prices than selling at the local farmers' market. It depends on local market characteristics.

Table 5. Comparative Static – Tomato Price.

Technological Combination	**Expected Tomato Price**		
	$2.11/lb	**$2.67/lb**	**$3.23/lb**
Mean NPV coupled w/out co-product	$45,925	$87,505	$129,085
Mean NPV coupled w/co-product	$47,842	$89,422	$131,003
Mean NPV de-coupled w/out co-product	$97,906	$153,805	$209,707
Mean NPV de-coupled w/co-product	$100,700	$156,599	$212,501

Similarly, Table 6 summarizes comparative static results for a change of tilapia prices by one standard deviation above and below the mean across the four technological combinations. Tilapia price fluctuations impacted the NPV of each technology, but the impact was smaller than that of tomatoes despite having a larger standard deviation. This means that while consumers' willingness to pay for locally produced tilapia matters, it is less of a driving factor than tomatoes. This is unsurprising since the present value of tilapia revenue across all systems is only $60,052. Conversely, the present value of tomato revenue is $266,525 in decoupled and $198,304 in coupled systems. Tilapia adds its real value to aquaponics operations in the sense that it reduces fertilizer cost and increases tomato price by allowing for an organic certification.

Assuming tilapia as the fish choice in both systems was necessary due to the lack of existing data for other fish under the technologies considered. It also allows this research to focus on the technological combinations themselves. However, there are implications to that assumption. Coupled systems run a compromised water pH for both fish and plants, making it challenging to raise high-value sensitive fish like trout or salmon. An advantage of decoupled systems is that their increased control over pH avoids this compromise. This makes raising higher priced sensitive fish such as salmon or trout easier. Superior Fresh follows this strategy with a modified decoupled system that treats and recirculates 99% and discharges the other 1% of its water (Superior Fresh, 2020). This increased control over water pH allows it to successfully raise salmon.[3]

Table 6. Comparative Static – Tilapia Price.

Technological Combination	Expected Tilapia Price		
	$1.37/lb	$2.68/lb	4.00/lb
Mean NPV coupled w/out co-product	$58,039	$87,505	$117,083
Mean NPV coupled w/co-product	$59,956	$89,422	$119,000
Mean NPV de-coupled w/out co-product	$124,341	$153,805	$183,384
Mean NPV de-coupled w/co-product	$127,135	$156,599	$186,179

The literature varies in labor cost assumptions. Bailey et al. (1997) claimed an operation of similar size to ours requires one manager. Simonetti (2015) argues that an aquaponics plant roughly three times the size of ours requires one manager and one employee. In other cases, volunteers support production. The University of the District of Columbia implemented an aquaponics facility run by community volunteers and supervised by the college's land-grant centers (O'Hara, 2015). A manager may require varying levels of labor, depending on community or university involvement, knowledge of aquaponics, and ability to work for themselves. Table 7 compares the expected NPV of an operation which requires a manager, a manager plus an additional part-time worker, and a manager plus an additional full-time worker. We followed the literature and assumed the full-time manager/owner, present in all cases, was the residual claimant of any positive NPV, and paid themselves based upon that (Bailey et al., 1997; Simonetti, 2015; Tokunaga et al., 2015). Paid labor is the amount of labor that is required in addition to the manager's time.

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[3] Coupled and decoupled systems do not always follow a neat dichotomy. Superior Fresh's system is decoupled because it treats the water before going back to the fish tanks. This separates each subsystem and allows control over each. They pay for this control with higher capital and electricity costs, but could instead use more fresh water.

Table 7. Comparative Static – Labor.

Technological Combination	Additional Paid Labor Requirement		
	None	1 part-time worker	1 full-time worker
Mean NPV coupled w/out co-product	$87,505	$20,267	-$46,971
Mean NPV coupled w/co-product	$89,422	$22,184	-$45,053
Mean NPV de-coupled w/out co-product	$154,262	$86,568	$19,331
Mean NPV de-coupled w/co-product	$156,601	$89,363	$22,125

Labor requirements greatly affect the economic viability of all technological combinations. The decoupled system is more resilient in maintaining its economic profitability under higher labor requirements than the coupled system, but decreases 86% with even one additional full-time worker. The economic reality is even less favorable if one considers the manager's opportunity cost. Managing an aquaponic facility requires a certain degree of knowledge and skill. For the operation size considered, an aquaponics manager would likely achieve a higher expected return working in a different industry over the 15-year project life. For an aquaponics manager to receive a satisfactory return on their labor, they would either need to operate in markets with high prices for organic, locally, and sustainably grown fish and vegetables, locations that value aquaponic community or university involvement, or a larger operation.

In Table 8 we summarize the comparative statics on the discount rate to allow potential investors to specify their own desired rate of return. Previous NPV analyses in literature used discount rates from 6% (Simonetti, 2015) to 20% (Bailey et al., 1997). Higher discount rates made all projects less attractive This is unsurprising due to the relatively large upfront investments and steady stream of income over time associated with aquaponics operations.

Changing the expected level of tomato price, tilapia price, labor requirement, and discount rate all had a meaningful effect on the expected NPV of each technological combination. This was especially true for the level of hired-labor requirement. None of these comparative statics, however, changed the optimal technological combination. The only possible scenario considered that could make a manager prefer a coupled system to a decoupled system is one in which the variable cost of water becomes over 20 times more expensive than it currently is for a plant operating in Park City. Due to the controlled environment within aquaponics, yield variability is low and is not expected to affect the outcome of the investment barring extenuating circumstances.

Table 8. Comparative Static – Discount Rate.

	Mean NPV of Technological Combination			
Discount Rate	**Coupled w/out co-product**	**Coupled w/co-product**	**De-coupled w/out co-product**	**De-coupled w/co-product**
5%	$138,103	$140,912	$228,581	$232,587
6%	$125,917	$128,512	$210,578	$214,292
7%	$114,889	$117,289	$194,281	$197,732
8%	$104,885	$107,108	$179,497	$182,707
9%	$95,790	$97,853	$166,054	$169,047
10%	$87,505	$89,422	$154,262	$156,601
11%	$79,941	$81,725	$142,623	$145,236
12%	$73,021	$74,683	$132,391	$134,838
13%	$66,673	$68,229	$123,010	$125,306
14%	$60,852	$62,300	$114,393	$116,549
15%	$55,491	$56,844	$106,462	$108,489

Discussion

The results of our TEA and comparative static analysis imply that a decoupled aquaponics system paired with fertilizer capture represents the most economically attractive technological combination from the options considered in this analysis. These results hold true across the range of parameters for price, input cost, discount rate, and labor considered. This takeaway provides a degree of generalizability in optimal technological selection across a range of market primitives, meaning that decoupled systems with fertilizer co-product capture will provide the highest expected return of the technologies considered for tomato and tilapia production across a range of locations. This gives aquaponic managers a technological basis for optimal plant management.

The primary consideration for aquaponics plant feasibility is labor cost. Even favorable labor estimates state that aquaponics is labor-intensive, requiring one full-time manager. Under baseline assumptions, the most profitable combination provides an NPV of $156,601 for which the manager is the residual claimant. This is the equivalent to a yearly salary of $20,589 over 15 years. A full-time manager running an intermediate commercial-scale plant is unlikely to find success in aquaponics. However, aquaponic production may still be economically desirable in two situations. The first, there is a positive relationship between consumer income and willingness to pay for food attributes such as organically and sustainably produced, and locally grown. If a plant locates in a region of high consumer income or can contract with an upscale restaurant specializing in such goods, the aquaponics plant will receive a price above the baseline assumptions for tomatoes and tilapia in this analysis.

The second, the most successful aquaponics operations are among the largest in the world, such as Superior Fresh, Ourobros Farms, and Rogue Aquaponics. Studies by Quagrainie et al. (2018) and Bailey et al. (1997) argue that aquaponic production experiences considerable economies of scale. Quagrainie et al. (2018) reported the per unit cost of producing tilapia and basil to decrease by 18% when increasing the scale of an aquaponics plant from 5,000 lbs. of tilapia per year to 10,000 lbs. of tilapia per year (our aquaponic unit is 2,946 lbs. per year). This reduction in per unit cost was driven by an increasing marginal product of labor. Doubling the output of tilapia and basil only required a total of 31.2 hours of labor in comparison to 24 hours of total labor under initial conditions. In other words, increasing labor input by 36% doubled the amount of output.[4] If we applied the same assumption to our analysis doubling aquaponic capacity (to 5,892 lbs. of fish per year) at a decoupled fertilizer capture plant, the NPV would increase to $379,356 under baseline assumptions. This results in a more attractive yearly managerial salary of $49,875 for a plant that is still smaller than industrial scale.

From our analysis, we ascertain that labor is the primary variable for dictating aquaponic profitability. While aquaponics is not profitable enough to incentivize managers to enter full-time aquaponic production for a mid-size commercial plant, it becomes more attractive in high-value markets and larger operations. While we do not have existing data to quantify the economies of scale that would occur for each technological combination considered in this study, it would be surprising if economies of scale were substantively different from those explored by Quagrainie et al. (2018) and Bailey et al. (1997). It would also be surprising if it changed the optimal technological selection. The difference in expected NPV between the two system designs will still be driven by tomato yield versus water cost. Coupled and decoupled systems of the same size have similar labor and capital requirements so both technologies should experience similar economies of scale.

Conclusions

Worldwide agricultural practices will need to adjust to the resource constraints enforced by nature in order to meet food security demands in the future. The ability to produce more food under tightening economic, environmental, and social constraints is a vexing problem for which aquaponics offers a solution. This article gives a road map to the

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[4] We assumed constant manager time commitment and that paid workers provided the 36% increase in labor.

technological combination offering the highest odds of success—decoupled systems with fertilizer capture. Tomato and tilapia prices each have a large effect on a project's expected NPV. However, the most important factor is the labor requirement. Projects requiring large amounts of labor or expensive labor are not viable. It is unlikely that even the best technology available would give managers a sufficient return for their time to operate an intermediate commercial-scale plant considered in this study. However, doubling the plant size would make aquaponic production more attractive under baseline assumptions, if the technologies considered in this study experience similar economies of scale to the system found by Quagrainie et al (2018).

Further economic research on aquaponics is necessary. Our analysis focused on a technological choice that was likely to have a large effect on economic viability, while allowing direct comparison across all four combinations considered. While the decisions we analyzed are important for aquaponic plant profitability, dozens of other important technological/managerial decisions warrant further research. Choices between subsystem layouts, subsystem technologies such as growing-bed medium, or other co-product streams such as charging for tours of the plant are a few of the decisions that could additionally affect profitability.

The literature could also benefit from more studies optimizing fish and vegetable choices. We assumed tomatoes and tilapia for aquaponic production as they were the most popular in the literature and were the given choice in the studies used to retrieve our technological parameters. Swapping different combinations of plants and fish into our analysis wouldn't have allowed us to hold all else constant while comparing technologies. However, aquaponic technology can grow different crops than tomatoes such as basil or lettuce. A wide range of fish species are possible as well; Superior Fresh currently raises Atlantic salmon. It sells processed salmon cuts at approximately $21/lb. (over 7.4 times the price of tilapia). Different species of plants and fish have different growth rates and associated costs than tomatoes and tilapia and warrant their own independent analysis. Additional cost benefit analyses quantifying the economies of scale associated with specific aquaponic technologies would also be helpful. Expanding an aquaponic manager's insight into optimal choice of technology, crop, fish, and scale provides the best opportunity for investments to be successful. These studies would also enhance the potential for aquaponics to run operations that are profitable, sustainable.

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