Economic Analysis of an Aquaponic System for the Integrated Production of Rainbow Trout and Plants

P.R. Adler[1], J.K. Harper[2], E.M. Wade[3], F. Takeda[1], and S. T. Summerfelt[3]

[1] USDA-ARS
45 Wiltshire Road
Kearneysville, WV 25430

[2] Department of Agricultural Economics and Rural Sociology
The Pennsylvania State University
214-A Armsby Building
University Park, PA 16802

[3] The Conservation Fund's Freshwater Institute
P.O. Box 1746
Shepherdstown, WV 25443

ABSTRACT

Conventional treatment alternatives for phosphorus in wastewater, whether they employ chemical precipitation, physical removal, or land application technologies, represent a significant additional cost to the owner of an aquaculture operation. Plant-based removal of nutrients has the potential to generate additional revenues, which can offset treatment costs. The objective of this analysis was to describe the economic relationship between a 22,680 kg per year recirculating rainbow trout (*Oncorhynchus mykiss* Walbaum) production system and a hydroponic treatment unit, growing 'Ostinata' lettuce (*Lactuca sativa* L.) and sweet basil (*Ocimum basilicum* L.), capable of reducing phosphorus concentration levels in the fish farm effluent to less than 0.1 mg/L. The integration of the fish and plant production system (aquaponics) produces economic cost savings over either system alone. Shared cost savings come from spreading out operating costs (e.g., management, water, nutrients, and overhead charges) and capital costs (e.g., backup generator, used truck, and office equipment) over the two systems. The investment analysis demonstrates the profitability of this combined system over its 20-year expected life. Net present values are positive for a wide range of discount rates. Internal rate of return analysis shows that for a total investment of $244,720 this system can potentially provide a return of 12.5%. The hydroponic system drives the potential profitability of the combined system with 67% of annual returns derived from plant production.

INTRODUCTION

Consumer demand for fish has been increasing, but ocean fish catches continue to decline. Aquaculture, the cultivation of freshwater and marine plants and animals, is one of the fastest growing segments of U.S. agriculture. The increase in farm-raised fish is leading to increased concerns regarding discharges from those facilities. Therefore, treatment of fishery effluents needs to be considered when planning aquacultural production systems. Aquacultural effluents are difficult to treat because of large volume flows carrying relatively dilute nutrients (< 1 mg/L P) (Adler et al. 1996e; Heinen et al. 1996a). However, it may be important to treat the nutrients in aquaculture effluents because, depending on the quality of receiving water, the total nutrient mass loading can contribute significantly to environmental degradation. Land-based recycle aquaculture facilities release dissolved nitrogen and phosphorus to the water environment, which contributes to the undesirable growth of macro and micro algae in receiving waters. All states in the Northeastern U.S. have regulations regarding the discharge of aquacultural effluents (Ewart et al. 1995). Technologies are available to reduce the concentration of nutrient discharge from these facilities to regulated levels based on United States EPA (Environmental Protection Agency) water quality drinking standards. Some common solutions to reducing nutrient discharge include reducing excess phosphorus concentrations in the feed (Heinen et al. 1996a; Jacobsen and Borresen 1995; Ketola and Harland 1993), reducing the amount of uneaten feed entering the rearing system (Asgard et al. 1991; Summerfelt et al. 1995), aggressive separation of uneaten feed and feces from the waste stream (Summerfelt 1996), biological, chemical, and physical nutrient removal systems (Adler et al. 2000; Metcalf and Eddy Inc., 1991), and plant-based nutrient removal systems (Adler et al. 1996d,e; Adler 1998; Rakocy and Hargreaves 1993). Of these solutions, plant-based removal of nutrients has the potential to offset treatment costs with additional revenues (Adler et al. 2000). Byproduct utilization is an important strategy to enhance both the economic and environmental sustainability of aquaculture (Adler et al. 1996c).

Integrated hydroponic and fish production systems are an example of nutrient recycling which can reduce nutrient discharge to the environment and generate additional revenues. Economic analysis of warmwater fish species (eg., tilapia) of small research-scale (Jenkins et al. 1996; Jenkins and Wade 1997) and commercial-scale (Bailey et al. 1997) systems have been published. In these types of systems, fish-rearing water is applied to plants that absorb dissolved nitrogen and phosphorus from the water. The water is then returned to the fish-rearing unit for reuse. This technology is impractical, however, in coldwater recycle systems (e.g., rainbow trout, arctic charr) due to temperature elevation in the plant treatment phase. For this reason, plant-based nutrient removal from coldwater fish rearing systems must take place after final discharge from the fish rearing system.

Hydroponic production of lettuce and basil using thin-film technology, also known as NFT - Nutrient Film Technique, was investigated as a method to remove P to low levels from an aquaculture effluent. Thin-film technology is a hydroponic crop production system in which plants grow in water that flows continuously as a thin film over their roots. Water flow across the roots decreases the stagnant boundary layer surrounding each root which, in turn, enhances the mass transfer of nutrients to the root surface and permits crops to maintain high productivity at steady-state P levels above 0.3 mg/L (Chen et al. 1997). The rainbow trout effluent in this study contained between 0.5 and 0.7 mg P/L. So, conventional hydroponic technology (where all plants in the trough are the same age) could only remove about 50% of the P while producing a marketable product. Although lettuce produced using NFT can remove P to <0.3 mg/L, a reduction in growth will coincide with a further reduction in solution P concentrations. A conveyor production system made it possible for plants to remove >95% of the P (to < 0.01 ppm P) in the rainbow trout effluent while producing a marketable product.

The objective of this analysis was to describe the economic relationship between a 22,680-kg per year recirculating trout production system and a hydroponic treatment unit capable of reducing phosphorus concentration levels in the fish farm effluent to less than 0.1 mg/L. Adler et al. (2000) conducted a study which compared the cost of alternative nutrient discharge treatment options including chemical and filtration methods and hydroponics. However it did not describe the economic relationship between the fish production system and the greenhouse treatment system as a combined business enterprise. The economics of this integrated relationship must be quantified to properly assess the viability of this technology.

MATERIALS AND METHODS

The economic feasibility of a small-scale trout production system with an associated hydroponic treatment system was evaluated using data from studies conducted at the Conservation Fund's Freshwater Institute during 1994 and 1995. Inputs for the fish production system are based on United States Department of Agriculture (USDA) sponsored research evaluating water reuse technologies for cold water trout culture (Hankins et al. 1995; Hankins et al. 1996; Heinen et al. 1996b). Inputs for the hydroponic treatment system are based on USDA-ARS (Agricultural Research Service) research designed to economically reduce nutrient discharge from a cold water trout production system (Adler et al. 1996b).

Rainbow Trout Production System

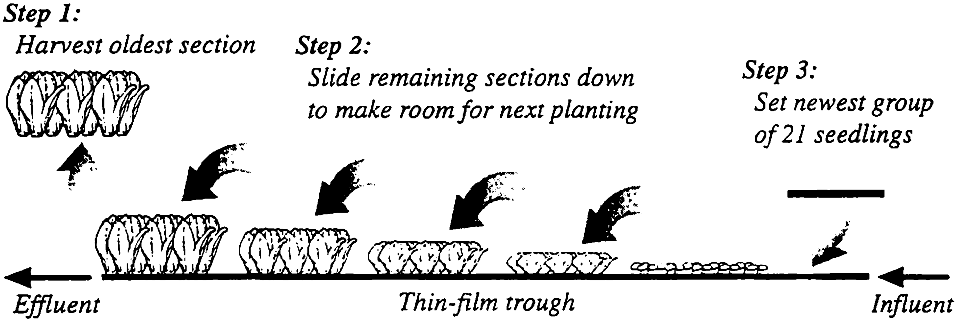
The Freshwater Institute maintains a high-density recirculating rainbow trout production facility near Shepherdstown, WV, USA. The facility evaluated in this analysis utilizes intensive water reuse production technology. Approximately 109 m^3 of trout effluent are produced daily. All fish production takes place inside an insulated metal building (239 m^2). The production system consists of 2 independent fish rearing systems composed of a single fish tank and filtration loop. The fish tanks are cross flow raceways (19,000 L). The filtration loops include drum filters, fluidized sand filters, carbon dioxide strippers, and low head oxygenators (Figure 2). The production schedule utilizes a continuous stocking strategy where 10.2-cm fingerlings are stocked every two months and size graded harvests of the largest fish are made on a weekly basis. Approximately 10% of the system biomass (431 kg) of market size fish are harvested weekly. The mean full production cycle per stocked cohort is ten months. The average production per year at steady state is 22,680 kg of market size fish.

Rainbow Trout Effluent Characteristics

The bulk effluent from the recirculating system for rainbow trout production at The Conservation Fund's Freshwater Institute typically has a pH of 7.2 and contains about 6 mg/L total suspended solids (TSS) and the following macronutrients (mg/L): NO_3-N (25), P (0.7), K (5), Ca (55), Mg (20), and S (9). In contrast, the spring water that supplied the fish culture system typically contained (mg/L): NO_3 (3), P (<0.001), and K (3). In this effluent, nutrients most limiting to plants (in decreasing order) are Fe, Mn, Mo, and K. A plant's productivity is determined by the nutrient present in lowest supply relative to its requirements. When other nutrients limit plant growth, P removal can be increased by adding those nutrients that are most limiting. To maximize P removal, the following nutrients were added to make P the most limiting nutrient: 0.1 mg/L Fe-EDDHA (LibFer SP, Allied Colloids Inc., Suffolk, VA, USA), 0.1 mg/L Mn-EDTA (Librel Mn, Allied Colloids Inc., Suffolk, VA, USA), 0.004 mg/L Mo (as $(NH_4)_6Mo_7O_{24}$), and 15 mg/L K (as K_2SO_4).

Conveyor Production System

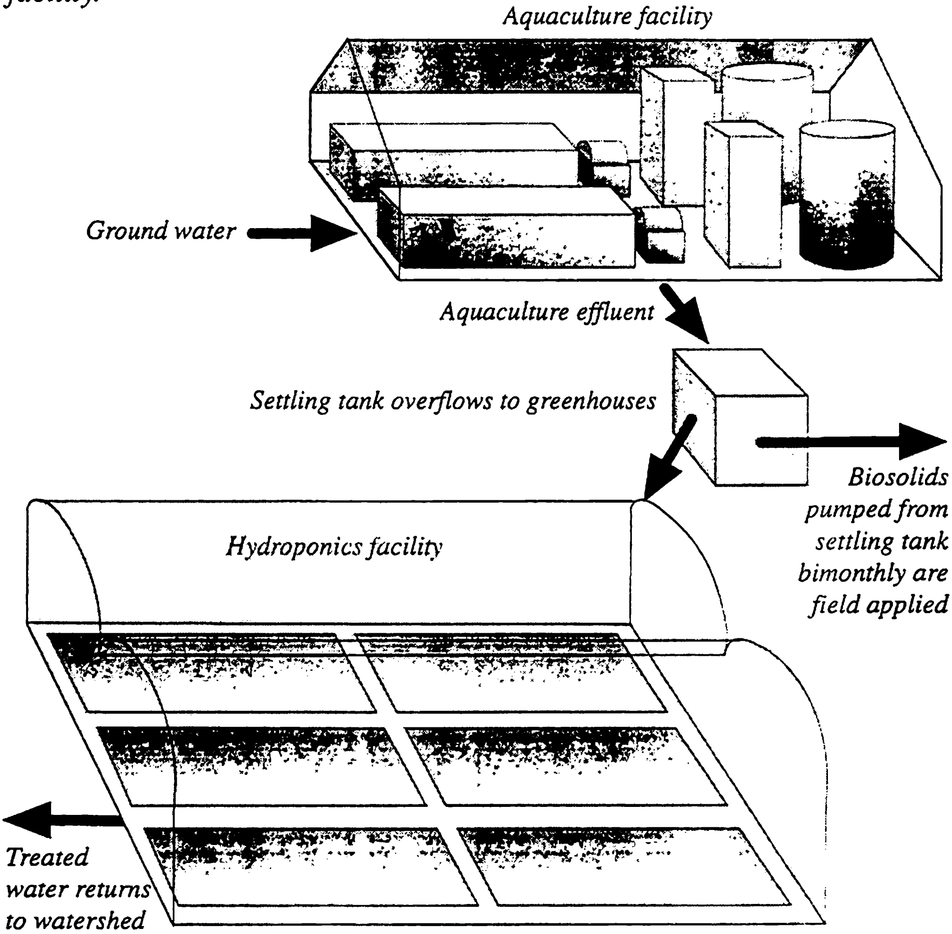
Figure 1. Conveyor crop production schematic for hydroponic lettuce and basil.



'Ostinata' lettuce (*Lactuca sativa* L.) and sweet basil (*Ocimum basilicum* L.) were seeded into Oasis® cubes (Smithers-Oasis, Kent, OH, USA). The lettuce and basil seedlings were placed into thin-film troughs and watered for the first 20 days with a recirculated complete nutrient solution (Adler et al. 1996e). After about 3 weeks lettuce and basil were moved to a nonrecirculating thin-film system configured with the conveyor production sequence. Adler et al. (1996e) describe the system in more detail. With the conveyor production strategy, seedlings are set at time intervals (e.g., every 4 days) near the inlet of a thin-film system and progressively moved in sequence as they matured towards the outlet (Figure 1). This cycle is repeated 6 times to move a given set of plants completely through the system to harvest. The number of sections can be greater or less than 6. Increasing the number of sections decreases the percentage of biomass removed with any one harvest and results in a more stable outlet concentration.

Plants have the capacity to absorb and store nutrients in excess of their immediate needs, a process called luxury consumption (Marschner 1995). The conveyor crop production strategy enables plants to store P early in their growth cycle (when they are younger and closer to the inlet where the P concentration is higher). This stored reservoir of P can be remobilized to meet current plant needs and supplement the lower P

Figure 2. Schematic of the integrated fish and hydroponic plant production facility.



influx rate, which occurs as P drops below about 0.3 mg/L in the effluent. Phosphorus remobilization will maintain growth as long as the tissue P concentration remains above the critical deficiency level (about 0.35-0.4% P on a dry weight basis in lettuce). At the front end of the thin-film troughs, where nutrient concentrations were highest, young plants absorbed and stored nutrients in excess of their immediate needs. Luxury consumption of nutrients during this early growth phase sustained the plants later when they were moved towards the trough outlet where nutrient concentrations in solution were too low for absorption kinetics to meet their growth needs. Cellular nutrient concentrations were sufficient to sustain growth even after nutrients within the flow were limiting.

This conveyor crop production system permitted the removal of P to very low levels (ppb), without an apparent reduction in plant productivity (Adler 1998). This is in contrast to a conventional production system where a gradient in growth and a reduction in plant quality would accompany the reduction in nutrient levels. Using the conveyor production strategy, lettuce and basil were able to remove dissolved P levels to less than 0.01 mg/L and developed to a marketable product with no apparent reduction in productivity.

Because plants remove nutrients continuously, effluent storage facilities are not necessary to temporarily hold effluents that are generated 24 h a day. Previous research found that N absorption varied with the day/night cycle while P absorption has very little diurnal variation (Adler et al. 1996a).

Sizing Criteria for Greenhouse Hydroponic System

Greenhouse sizing assumptions for this analysis are based on the plant mass required to reduce the concentration of the phosphorus in the fish system effluent to a level of 0.1 mg/L (Adler et al. 2000). After solids collection, the recycle fish system discharges 22.6 kg of phosphorus a year (Heinen et al. 1996a). Research has shown that using a hydroponic system, phosphorus concentrations can be reduced from 0.6 mg/L to 0.1 mg/L in the greenhouse. Nitrate concentrations can be reduced from 15 mg/L to 6 mg/L, well below the 10 NO_3-N mg/L allowable limit for nitrate in drinking water. Optimal placement for a greenhouse treatment system would be downhill from the fish facility to take advantage of gravity to move the water from one to the other (Figure 2).

The hydroponic treatment system consists of a complete greenhouse facility capable of year round plant production. A system capable of treating the daily effluent from production of 22,680 kg of trout would require 3, 9.1 m x 40.2 m arch-style greenhouses. In addition to a hydroponic trough rearing system for the plants, greenhouses were assumed to include cooling and heating systems and supplemental lighting (Adler et al. 2000).

Table 1. Component fixed costs of the fish production system.

Fish system components	**Estimated fixed cost ($U.S.)**	**Projected life (years)**
Building	43,300	20
Plumbing general	13,000	5
Oxygen equipment	10,700	5
Tanks	10,000	20
Drum filters	9,200	5
Fluidized sand filter	7,800	20
Furnace and heating	5,200	10
Feeders/nets, etc.	4,600	5
Well pump	4,300	5
Computers/phones	4,000	3
Monitor and controls	3,800	5
CO_2 stripper	2,400	20
Hatchery equipment	2,300	10
Recirculating pumps	2,200	5
Total fish system	**$122,800**	

Table 2. Component fixed costs for the greenhouse structure and hydroponic system.

Greenhouse components	**Estimated fixed cost ($U.S.)**	**Projected life (years)**
Frames & sidewalls	13,430	20
Gable ends	2,400	20
Wood baseboard	560	10
Double polyethylene film (0.15mm)	2,350	3
Exhaust fans & vents	9,000	10
Heater	5,400	10
Crushed stone base	600	20
Light fixtures	18,480	10
Electrical installation	2,970	20
Lamps	6,470	8
Evaporative cooler	3,000	10
Construction costs	14,110	20
Total greenhouse system	**$78,770**	

Hydroponic components	**Estimated fixed cost ($U.S.)**	**Projected life (years)**
Tray supports	3,780	20
Hydroponic trays & covers	7,990	10
Supply line	260	5
Feeder tubes & fittings	1,410	5
Injector pumps	1,650	5
Solenoid valves	280	5
Nutrient tanks	90	5
Submersible pumps	1,690	5
Total hydroponic system	**$17,150**	
Total greenhouse and hydroponics system	**$95,920**	

Table 3. Combined facility fixed costs.

Facility components	Fixed costs ($U.S.)
Fish system	122,800
Greenhouse system	95,920
Backup generator (50-kilowatt)	21,000
Office equipment	2,000
Land	3,000
Total combined system	**$244,720**

ECONOMIC ANALYSIS

Evaluation of the economic viability of the combined fish production and greenhouse hydroponic system requires the consideration of initial and replacement capital costs, annual operating costs, and annual revenues. The flow of costs and returns over the projected 20-year life of the system were evaluated using investment choice criteria including net present value (NPV), internal rate of return (IRR), and payback period.

Fixed Costs

The initial fixed costs for the fish production system total approximately $122,800 (Table 1). The total initial fixed costs for the greenhouse and hydroponic system is about $95,920 (Table 2). As indicated by the expected life of the individual components, many items will need to be replaced over the course of the 20-year investment. A component with a 3-year expected life will need to be replaced 6 times; with a 5-year life, 3 times; with an 8-year life, 2 times; and with a 10-year life, 1 time. Combined system costs, including capital items shared by both systems (office equipment, backup generator, and land) are summarized in Table 3.

Annual Variable Costs

Annual variable costs for the combined system are presented in Table 4. Approximately 60% of the combined system costs represent employee

Table 4. Annual variable costs of the greenhouse and fish systems.

Fish system	**Variable costs ($U.S.)**
Labor	25,000
Feed	23,300
Energy	17,440
Transportation	2,000
Maintenance	1,500
Fish eggs	880
Overhead (at ~2%)	1,400
Total fish system	**$71,520**

Greenhouse system	**Variable costs ($U.S.)**
Harvest materials	12,290
Energy	26,510
Labor	113,130
Seeding materials	10,890
Transportation and marketing	16,290
Fertilizer and pesticides	540
Overhead (at ~2%)	3,590
Total greenhouse system	**$183,240**

Total system variable costs	**Variable costs ($U.S.)**
Fish system	71,520
Greenhouse system	183,240
Manager	35,000
Total	**$289,760**

Table 5. Estimated annual revenues, expenses, and cash flows for a 20-year fish and hydroponic production system investment.

Year	Annual fixed cost ($U.S.)	Annual revenues ($U.S.)	Tax-deductible expenses[1] ($U.S.)	After-tax income[2] ($U.S.)	Annual cash flow[3] ($U.S.)
1	244,720	236,422	313,554	-53,338	-298,058
2	0	351,392	351,392	61,632	61,632
3	0	351,392	351,392	61,632	61,632
4	6,350	351,392	315,010	48,390	42,040
5	0	351,392	313,554	54,333	54,333
6	53,180	351,392	313,554	1,153	-52,027
7	6,350	351,392	313,554	47,983	41,633
8	0	351,392	313,554	54,333	54,333
9	6,470	351,392	313,554	47,863	41,393
10	6,350	351,392	313,554	47,983	41,633
11	53,180	351,392	313,554	1,153	-52,027
12	0	351,392	313,554	54,333	54,333
13	6,350	351,392	313,554	47,983	41,633
14	0	351,392	313,554	54,333	54,333
15	0	351,392	313,554	54,333	54,333
16	59,530	351,392	313,554	-5,197	-64,727
17	6,470	351,392	313,554	47,863	41,393
18	0	351,392	313,554	54,333	54,333
19	6,350	351,392	313,554	47,983	41,633
20	0	351,392	313,554	54,333	54,333

[1] *Includes cash costs, depreciation, and allocation of net operating loss from year 1 in years 2-4.*

[2] *Revenues minus cash operating expenses and taxes (15% on taxable income up to $25,350 and 28% on amounts above $25,350, but less than $61,400).*

[3] *After-tax income minus annual investment.*

Table 6. Net present value (NPV), internal rate of return (IRR), and payback period for the integrated trout and basil/lettuce production system.

Discount rate	NPV
4%	$266,139
6%	$176,797
8%	$107,580
10%	$53,197
IRR:	12.5%
Payback period:	7.5 years

payroll expenses (for hourly laborers and the system manager). Energy costs (for fuel and electricity) account for 15% of the combined system costs. Costs relating solely to the greenhouse system constitute 63% of the total system cost, reflecting the large amount of labor required by this system.

Annual Revenues

Annual revenues for the combined system are based on the yearly sale of 22,680 kg of trout and 398,600 plants of lettuce and basil (assuming 95% packout). Annual revenues for the hydroponic system are based on 50% production of lettuce and 50% production of basil. Annual revenues are estimated to be $236,422 in year 1 and $351,392 in years 2-20 (Table 5). Production of trout in year 1 is assumed to be only 25% of production in years 2-20 due to time required to get the fish system up to a steady state. Production of plants in the first year is reduced by 12% due to the time required to get the hydroponics systems up to a steady state. In years 2-20, revenues from basil and lettuce account for 67% of the annual total for the system. Prices of $14/box of lettuce (24 heads per box), $0.60/plant of basil, and $5.09/kg of trout were used to calculate annual revenues. The vegetable prices are conservative and reflect typical marketing efforts. The assumed price for trout is below the weighted average stocker price of $5.53/kg and is above the weighted average food fish price of $3.64/kg for the Northeast U.S. over the years from 1991 to 1995 (USDA-ERS 1996). Breakeven price analysis indicates that at steady state yield levels, prices could fall to $12.60/box for lettuce, $0.54/plant for basil, and $4.98/kg for trout and still cover the annual variable costs of production and depreciation expenses.

Investment Analysis

The purpose of an investment analysis is to demonstrate the profitability over the expected life of the investment. The economic viability of this combined fish and plant production system was evaluated using net present value analysis (NPV), which takes into account the time value of money and the variability of annual cash flows over time. The NPV method is used to reduce the 20-year stream of revenues and expenses from the combined system (Table 5) to a single number in which these future annual cash flows are discounted. A description of this method of analysis as it applies to fish farming projects is available in O'Rourke (1991).

NPVs of the combined system assuming various discount rates are found in Table 6. The NPV indicates the value of the investment in the combined system over its 20-year life in terms of today's dollars. For example, at a discount rate of 8%, the NPV of the combined system is $107,580. Lower discount rates increase the NPV because the value of future cash flows are reduced less than they would be for higher discount rates. Choice of an appropriate discount rate is up to the individual decisionmaker and depends on their preference for current versus future consumption, the cost of the investment capital (personal or borrowed funds), and the availability and riskiness of other investment opportunities. In selecting between competing investment opportunities, the decisionmaker would select the one that maximizes expected NPV.

The IRR is the discount rate that equates a project's initial cost with the sum of its discounted future cash flows. In other words, the IRR is the discount rate which would reduce the NPV of a project to zero. The results of the IRR analysis shows that for the initial investment of $244,720 this system can potentially provide a return of 12.5% over the life of the facility.

Another widely used investment criterion is the payback period. This is the length of time required to recover the initial fixed costs of an investment. According to this criterion, it will take approximately 7.5

years to recover the initial fixed costs of $244,720. Although widely used as an evaluation tool, the payback period approach has two major deficiencies: 1) it fails to consider the time value of money and 2) it ignores the length and magnitude of cash flows after the payback period. The payback period should not be used to compare investment alternatives unless they are of the same magnitude and expected life.

Cost and revenue estimates made in this analysis are conservative in order to offset production variability caused by potential production and marketing inefficiencies and occasional disease setbacks. Experienced commercial growers could potentially build and operate the system at higher levels of profit. The addition of the hydroponic production system results in significantly higher profitability than the fish system alone, especially when considering the cost of wastewater treatment, which could potentially be charged to the fish system. With only 39% of the total fixed cost and 63% of the total annual variable costs, the hydroponic system generates 67% of the annual revenue for the combined system. The revenue from the greenhouse system also helps offset first year operating losses from the fish system. The economics of the fish system could be improved by increasing the scale of production (Wade et al. 1996) and by the utilization of higher valued fish species such as arctic charr, which has similar production requirements and a higher market price than rainbow trout.

In addition to the economic benefits, there are non-monetary societal benefits associated with this type of system integration. There are the benefits of using recycle technology to reduce water consumption by the fish system; it uses only 3% of the water of traditional raceway technology. Also, the integration of the two systems reduces the combined consumption of water by reusing water discharged from the fish production system for plant production. Water reuse increased and the majority of this water is returned to the environment in excellent condition. This makes the combined systems largely non-consumptive and non-polluting users of the water resource.

This analysis demonstrates that the integration of recycle aquaculture systems with hydroponic vegetable production can generate a profit and still be environmentally friendly. These types of systems, when designed properly can reduce water use and greatly reduce the discharge of unwanted nutrients to the environment. Conventional treatment alternatives for phosphorus in wastewater, whether they employ chemical precipitation, physical removal, or land application technologies, represent a significant additional cost to the owner of an aquaculture operation. Treatment costs vary from a low of \$0.18/m^3 for land application using alfalfa as the recipient crop to a high of \$1.26/m^3 for reverse osmosis and electrodialysis (Adler et al. 2000). They also involve moderate to large investments in capital items that have no alternative uses. In contrast, the conveyor production system generates income while nutrients are removed to a very low level (Adler et al. 1996c,f). Treatment of fishery effluent using hydroponic crop production represents a potentially profitable additional enterprise for the aquaculture producer. Regardless of the crop chosen (lettuce or basil), expected crop prices appear to be more than sufficient to cover the costs of production at expected yields. The primary drawbacks of hydroponic production as a treatment alternative would be the added technical sophistication, labor, and marketing expertise required. Various production and market risks could significantly reduce the projected returns. These include fish and plant disease, mechanical failure, regulatory changes, and market variation. Development of marketing plans for both fish and produce is crucial. Sufficient attention must be paid to the day-to-day operation and the development and servicing of markets or the profitability advantage of combining the two production systems could rapidly disappear.

REFERENCES

Adler, P.R., Harper, J.K., Takeda, F., Wade, E.M., Summerfelt, S.T. Economic Evaluation of Hydroponics and Other Treatment Options for Phosphorus Removal in Aquaculture Effluent. *Hort Science* **2000**. (in press).

Adler, P.R. Phytoremediation of Aquaculture Effluents. *Aquaponics Journal* **1998**. 4(4):10-15.

Adler, P.R., Summerfelt, S.T. , Glenn, D.M., Takeda, F. Evaluation of a Wetland System Designed to Meet Stringent Phosphorus Discharge Requirements. *Water Environmental Research* **1996**a. 68(5):836-840.

Adler, P.R., Summerfelt, S.T., Glenn, D.M., Takeda, F. Evaluation of the Effect of a Conveyor Production Strategy on Lettuce and Basil Productivity and Phosphorus Removal from Aquaculture Wastewater. In: Staudenmann, J., Schönborn, A., and Etnier. C. (eds.), Recycling the Resource - Ecological Engineering for Wastewater Treatment. Proceedings of the Second International Conference, Waedenswil - Zurich, Switzerland; 18-22 September 1995. Trans Tech Publications, Switzerland. Environmental Research Forum **1996**b. 5-6:131-136.

Adler, P.R., Takeda, F., Glenn, D.M., Summerfelt, S.T. Utilizing Byproducts to Enhance Aquaculture Sustainability. *World Aquaculture* **1996**c. 27(2):24-26.

Adler, P.R., Takeda, F., Glenn, D.M., Wade, E.M.,Summerfelt, S.T., Harper, J.K. Phytoremediation of Wastewater Using Lettuce and Basil. *Proceedings of the American Society for Plasticulture* **1996**d. 26:253-258.

Adler, P.R., Takeda, F., Glenn, D.M., Wade, E.M.,Summerfelt, S.T., Harper, J.K. Conveyor Production Strategy Enhances Nutrient Byproduct Recovery from Aquaculture Wastewater, pp. 431-440, In: Libey, G.S., and Timmons, M.B. (eds.) Successes and Failures in Commercial Recirculating Aquaculture Conference Proceedings **1996**e. NRAES-98. Northeast Regional Agricultural Engineering Service: Ithaca, NY. July 1996.

Adler, P.R., Takeda, F., Glenn, D.M.,Wade, E.M., Summerfelt, S.T., Harper, J.K. Nutrient Removal: Ecological Process Sows a Cost-saving Idea for Enhancing Water Quality. *Water Environment & Technology* **1996**f. 8:23-24.

Asgard, T., Langaker, R.M., Shearer, K.D., Austreng, E., Kittelsen, A. Ration Optimalization to Reduce Potential Pollutants - Preliminary Results. *American Fisheries Society Symposium* **1991**. 10:410-416.

Bailey, D.S., Rakocy, J.E., Cole, W.M., Shultz K.A. Economic Analysis of a Commercial-scale Aquaponic System for the Production of Tilapia and Lettuce. pp. 603-612, In: Fitzsimmons, K. (ed.) Tilapia Aquaculture: Proceedings from the Fourth International Symposium on Tilapia in Aquaculture **1997**. NRAES, Ithaca, NY.

Chen, X.G., Gastaldi, C., Siddiqi, M.Y., Glass, A.D.M. Growth of a Lettuce Crop at Low Ambient Nutrient Concentrations: A Strategy Designed to Limit the Potential for Eutrophication. *Journal of Plant Nutrition* **1997**. 20:1403-1417.

Ewart, J.W., Hankins, J., Bullock, D. State Policies for Aquaculture Effluents and Solid Wastes in the Northeast Region. *NRAC Bulletin* No. 300 **1995**. Northeastern Regional Aquaculture Center, University of Massachusetts-Dartmouth.

Hankins, J.A., Summerfelt, S.T., Durant, M.D. Impacts of Feeding and Stock Management Strategies Upon Fish Production Within Water Recycle Systems. pp. 70-86, In: Timmons, M.B. (ed.), Aquacultural Engineering and Waste Management **1995**. Northeast Regional Agricultural Engineering Service, Ithaca, New York.

Hankins, J. A., Summerfelt, S.T., Durant, M.D., Weber, A.L., Summerfelt, S.R. Effect of Cohort Size Distribution on Production and Growth Within a Sequentially Stocked and Harvested Rearing System. p 41, In: Aquaculture America 1996. Arlington Texas, Book of Abstracts **1996**. World Aquaculture Society, Baton Rouge, Louisiana.

Heinen, J.M., Hankins, J.A., Adler, P.R. Water Quality and Waste Production in a Recirculating Trout-culture System With Feeding of a Higher-energy or a Lower-energy Diet. *Aquaculture Research* **1996**a. 27:699-710.

Heinen, J.M., Hankins, J.A., Weber, A.L., Watten, B.J. A Semiclosed Recirculating-water System for High-density Culture of Rainbow Trout. *The Progressive Fish-Culturist* **1996**b. 58:11-22.

Jacobsen, C., Borresen, T. Formulation of Fish Diets with Reduced Phosphorous Content. *Water Science Technology* **1995**. 31(10): 167-173.

Jenkins, M.R., Wade, E.M., Yohn, C.W. The Opportunity for Small-scale Aquaculture as an Alternative Farm Enterprise: An Economic Analysis of a Small-scale Partial Reuse Trout Production System in West Virginia. *Journal of the ASFMRA* **1996**. p. 81-89.

Jenkins, M.R., Wade, E.M. A Preliminary Economic Analysis of a Low-cost, Small-scale, Natural Gas Powered, Integrated Recycle Aquaculture-hydroponic System for Tilapia. In: Fitzsimmons, K. (ed.), Tilapia Aquaculture: Proceedings from the Fourth International Symposium on Tilapia in Aquaculture **1997**. NRAES, Ithaca, NY.

Ketola, H.G., Harland B.F. Influence of Phosphorus in Rainbow Trout Diets on Phosphorus Discharges in Effluent Water. *Transactions of the American Fisheries Society* **1993**. 122, 1120-1126.

Marschner, H. Mineral Nutrition of Higher Plants. 2nd ed. Academic Press. Harcourt Brace & Co. **1995**. London, England. p. 466.

Metcalf and Eddy, Inc. Wastewater Engineering: Treatment, Disposal, and Reuse, Third Edition, revised by Tchobanoglous, G. and Burton, F.L. **1991**. McGraw-Hill, Inc., New York, NY.

O'Rourke, P. D. Current Status on Profits in Recirculating Systems. pp. 65-99, In: Regional Workshop on Commercial Fish Culture Using Water Recirculating Systems **1991**. IL-IN-SG-E-91-8. Illinois/ Indiana Sea Grant, Illinois State University, Normal, Illinois.

Rakocy, J.E., Hargreaves, J.A. Integration of Vegetable Hydroponics with Fish Culture: a review. pp. 112-136, In: Wang, J.K. (ed.), Techniques for Modern Aquaculture **1993**. ASAE, St. Joseph, MI.

Summerfelt, S., Holland, K.H., Hankins, J.A., Durant, M.D. A Hydroacoustic Waste-feed Controller for Tank Systems. *Water Science and Technology* **1995**. 31(10):123-129.

Summerfelt, S.T. Engineering Design of a Water Reuse System. pp. 277-309, In: Walleye Culture Manual, Summerfelt, R.C. (ed.), NRAC Culture Series 101 **1996**. Central Regional Aquaculture Center Publication Center, Iowa State University, Ames, IA.

United States Department of Agriculture, Economic Research Service. Aquaculture Situation and Outlook Report. USDA-ERS, Commodity Economics Division **1995**. Washington, D.C.

Wade, E.M., Summerfelt, S.T., Hankins, J.A. Economies of Scale in Recycle Systems, pp. 575-588, In: Libey, G.S., and Timmons, M.B. (eds.), Successes and Failures in Commercial Recirculating Aquaculture Conference Proceedings **1996**. NRAES-98. Northeast Regional Agricultural Engineering Service: Ithaca, NY. July 1996.