Sustainable intensive fish farming: The prospects of aquaponics

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Sustainable intensive fish farming: The prospects of aquaponics

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Background and motivation

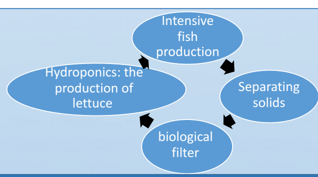
i. The flow of goods and waste gained interest in recent years, and is one of the core ideas behind the bioeconomy.
ii. Since the beginning of the 21st century scholars have explored the benefits of using waste to generate energy (i.e., biofuels and bioelectricity).
iii. While focusing on aquaculture as an example, this work explores the economic and environmental benefits of utilizing waste when managing livestock.
iv. Why aquaculture and hydroponics as an example: Aquaculture, the farming of aquatic animals under controlled conditions, has exhibited one of the world's highest growth rates of agricultural products in recent decades, with its share in global fish output growing annually at an average rate of 8.8% from 1980-2010 (FAO, 2012).
   1. Given this current average rate of 8.8%, output from fish farming is expected to surpass output from commercial fishing by 2018 (FAO, 2012).
   2. The aquaculture system is a reliable technology that generates a constant supply of fish at an efficient rate of feed-output ratio when compared to other livestock technologies (Ebeling, 2000).
   3. With extensive fish farming, nature consumes the uneaten food and high concentrations of nitrogen and phosphorus emitted during farming.
   4. Some of the extensive aquaculture systems date back to the Han dynasty (206 AC to 225 BC; Edwards (2004))
   5. However, intensive fish farming generates wastewater that contains residuals of uneaten food and high concentrations of nitrogen and phosphorus that harm the environment and can cause eutrophication (Klinger & Naylor, 2012; Lepisto et al., 2010; Losordo et al., 1999).
   6. The literature suggests the polluter pays principle, whereby the party responsible for producing pollution pays for the damage done (Folke et al., 1994; Folke et al., 1998, and references therein)
   7. Resulting in the fish supply contracting and the fish price increasing.

Conceptually, what is happening

- Two separate production processes, where *p* denotes output prices and *w* input prices.
- Aquaculture:
- Variable input: x_a.
  - For example, fish food
- Production process that results in output $y_a = f(x_a)$ (e.g., fish biomass), but that the production process also generates pollution, $z_a = Z(x_a)$.
  - In aquaponics, ammonia is a toxic by-product produced by the fish.
- The aquaculture grower's profit function is $\pi_a = p_{y_a} y_a - w_{x_a} x_a \underbrace{-w_{z_a} z_a}_{\substack{\text{assuming a cost to pollution} \\ \text{(e.g.,clean up costs)}}}$
- Hydroponics:
- Variable inputs: x_h.
  - For example, fertilizers
- Production process that results in output $y_h = h(x_h)$
  - e.g., lettuce or basil
- The hydroponics farm's profit function is $\pi_h = p_{y_h} y_h - w_{x_h} x_h$

Aquaponics: hydroponics and aquaculture

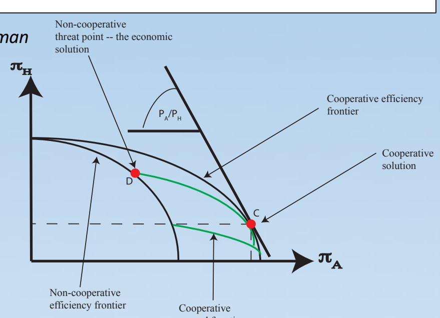
- The ammonia undergoes nitrification. The process occurs in a biological filter in which bacteria decomposes the toxic ammonia to nitrate.
- From the biological filter, water passes through the hydroponic component where the plants absorb nitrate and other nutrients used as fertilizer, thereby purifying the water which is returned to the fish.
- For simplicity and brevity, assume the two are perfect substitutes, that is, x_h and z are the same.
- Aquaponics (aquaculture + hydroponics): One's waste becomes the other's input



The equilibrium outcome: waste to input

- *Conceptually*
- Aquaponics systems lead to internalization of the negative externalities
  - Yielding larger output and thus lower prices
- Simple optimal decision rule that is based on limited amount of data
  - At the optimal harvest, the alternative cost of maintaining the fish-cycle for another period is equated to the marketing of the current fish-cycle
- *Cooperative:* One's waste becomes another's input
- *Human capital: growers invest in human capital and maintain the aquaponics system by themselves*

Cooperatives vs. the creation of human capital:



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Sustainable aquaponics systems

- The fish farmer does not consider the negative externalities created when raising fish.
- Regulation in the form of tax will address this social cost.
- **Alternatively**, the combination of fish farming and hydroponic growing of plants internalizes the externality, resulting in a sustainable solution.
- Combining aquaculture and hydroponic systems results in the pollution generated by the fish used as an input in the growing of plants – "one's waste is another's input."
  - The plant plays a role in the water purification process because it absorbs the nitrogen and phosphorus that is excreted into the water when raising the fish.
  - In addition, there is a decrease in production costs because of reductions in the use of fertilizer in the hydroponic systems, thus resulting in output that is larger than that of the unregulated system.

The bio-economic model

- The focus is on the continuous operation of several ponds.
- Time enters at two levels:
  - the age of the growing crop of fish
  - The calendar date of harvesting
- For a given age, the grower faces a dichotomous decision:
  - whether to sell the crop, or
  - to keep the existing crop and defer the sale decision to the next period.

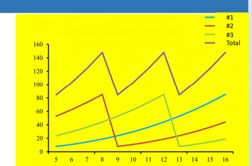
- The profit function of the fish grower $\text{Max}_t \pi(t) = (R_F(t) - C_F(t) - t * FC) * \frac{k_0}{t}$
- Where
  - Time (e.g., number of weeks) is denoted with t
  - Revenues from the marketing of fish: $R_F(t)$
  - Expenses that depend on number of fish: $C_F(t)$
  - Expenses that are fixed within the unit of time: FC
  - Horizon:

The single fish farmer solution:
- The solution suggests optimal harvest at t, where $\frac{dR_F(t^*)}{dt} - \frac{dC_F(t^*)}{dt} = \frac{R_F(t^*) - C_F(t^*)}{t^*}$
- The fish growing cycle ends when the fish farmer equates the marginal profit from marketing the fish with the average profit per unit of time.
- This relation is used to find the optimal harvesting age

Introducing the aquaponics system:
- internalization of the pollution using aquaponics.
- Assume that the cost of cleaning pollution is at least as high as the price of fertilizer
- Define the variables Rp as income from the sale of plants
- The profit function from this aquaponics system is $\text{Max}_t \pi = (R_F(t) + t * R_P - C_F(t) - t * FC) * \frac{k_0}{t}$

The empirical outcome: Tilapia and lettuce

We assume staggered production
1) Fish are grown in a number of containers, in parallel, where each container has fish of different age.
2) The idea is to minimize the biomass volatility, which also results in minimizing the effluents generated by the fish and the amount of fertilizers required by the plants



Regulation led to marketing the fish at an earlier age with a lower weight and thus lower total batch biomass: Profits go down yet fish price goes up!

When the grower takes into account external costs, the growing cycle is 32 weeks with fish weight of about 410 g

When the aquaponics system is employed, the growing period becomes 37 weeks with fish weight of 600 g

Assuming 40 tonne of fish per year results in a saving of 37,335 US$ per year

Conclusions

Key findings of the empirical analysis
- The choice of fish with a higher price per kilogram, such as mullet or barramundi whose consumer price is twice that of tilapia, can lead to a different distribution of income and increase the share of fish in revenue.
  - One can also grow ornamental fish such as koi, whose value per kilogram is even higher, thus increasing the income from fish farming further.
- The plants can also contribute to increasing a farmer's income through a combination of herbs, such as basil, which have a higher value and thereby reduce dependence on the demand for one product.

Barriers to the adoption of aquaponics and induced institutional innovation
- Combining fish farming with hydroponics requires expertise in both hydroponic and intensive fish farming.
- *Plausible solutions:*
  - Without the required knowledge of growing plants using hydroponics, the fish grower must hire an expert to take care of growing plants
- Creative developments of the supply chain of fish-farming can result in substantial increases to the profitability of fish-farming while minimizing its negative effect on the environment.
  - Requires the development of infrastructure/institutions that support such interactions
- There is a technical difficulty of creating a system that obtains an optimum growth environment for both the fish and plants.
- While nitrifying bacteria and plants thrive at certain PH levels, fish survive at different PH levels, creating ecological engineering challenges in the proposed closed system (Tyson et al., 2011).
- There is a need for
- Harnessing the ability to control the environment through precision technologies, and stabilizing and optimizing the environment using sensors and engineering.
- Use of vertical structures to grow plants, a technology that significantly reduces demand for land through the use of aquaponics systems.

Aquaculture results in rising demand of fish meals
- The need to feed farmed fish with fish meals strains wild fish populations, since it lead to imbalances in oceans via deteriorating shellfish populations in the oceans.
- However, alternative terrestrial plants rich in protein have been proposed to substitute for fish meals.
- Soybeans
- Sorghum
- And there are also aquatic plants such as duckweeds that can benefit the intensive fish farms beyond the saving of feeding costs that equal about 30% of the cost of managing the farms.