Aquaponics Research at RMIT University, Melbourne Australia

By Wilson Andrew Lennard

Sustainable farming is the farming of the new millennium. A lot of people see the sense in doing things sustainably, whether it be the way we build our houses or the way we run our farming enterprises. Sustainability means that we squeeze as much as we can out of a resource because these resources are limited and it is best to use them as efficiently as we can. It also means that we take the surrounding environment and ecology into due consideration. We protect it and care for it, because we understand that many of our resources come from this environment or ecology and, if we abuse it, we may eventually run out of those very resources we depend on. Aquaponics, as a hobby or a business enterprise, fits into this philosophy very well and this is why I am studying it.

As is well known, in aquaponics, the waste products from fish farming are used to grow plants. This is the first sustainable philosophy of Aquaponics…that fish waste is not seen as "waste," but as a "commodity." I am not sure about the rest of the world but, in Australia's urban area, fish farm effluent is seen as trade-waste. The disposal of trade-waste in Australia costs money and this extra cost lowers profit margins for the fish farmer. In rural areas, Australia enforces tight restrictions on any waste that may have an environmental impact. Our waterways are well protected and, subsequently, nutrient rich wastewater from fish farming is not allowed to be dumped into natural waterways. While it is recognized that recirculating aquaculture technology potentially lowers environmental impact from fish farming, wastewater discharge is still a problem.

Similarly, the use of water in Australia is coming under more strict control all the time. We are a dry country, the driest continent in the world! Freshwater resources are becoming a premium commodity in Australia, especially since global warming has affected our weather patterns (through El Nino induction) so we seem to be experiencing more regular droughts. Freshwater use and availability will definitely become more expensive in Australia in the coming years, as well as being vital to the sustenance of our environment.

These factors are all part of the philosophy that makes me interested in aquaponics.

I began my aquaponic research around two and a half years ago. The major question I am asking is…can aquaponic technology be adapted to Australian aquaculture?. This may seem a silly question because, as most of you know by now, aquaponics is a proven technology. If it works with other fish then it will work with Australian fish, which is exactly right. Science is not so accepting of common sense, though, and the scientific method requires that everything (that is EVERYTHING) must be proven or disproved. As you can imagine, I quickly proved experimentally that aquaponics works with Australian fish. There are, however, some very interesting side questions that may be posed within the context of the original question I posed above. These questions constitute the realm in which I am working.

One of the most interesting initial questions I asked myself was: what is aquaponics? By this I mean: what methodologies are considered aquaponics? This question can be answered without scientific enquiry because it is based on interpretation and philosophy. My feeling is that there are several advantages to aquaponics, such as water saving and the potential of zero environmental impact from wastewater discharge, that are at the core of what Aquaponics is. To me, a true aquaponic system is one that discharges as little, if any, wastewater to the environment and uses as little new, make-up water as possible. This means that aquaponics is a truly enclosed, recirculating system, where water from the fish is sent to the plants, the plants remove the nutrient and cleaned water is returned to the fish in a continuos cycle. You may ask…what other methodologies constitute aquaponics? There are systems around (even in Australia) where the waste-water from the fish is sent to the plants, used for plant growth in either a one pass system or a multi-pass system, then the water is released to waste without ever being returned to the fish. I agree that the water and waste nutrient is being used a second time and that this is a more efficient use of water than a fish-only system but, to me, it doesn't constitute aquaponics because it ignores two of the main advantages that should be inferred by aquaponics. They include low input water use and zero wastewater discharge. I, therefore, restricted my research to true, recirculating aquaponics only.

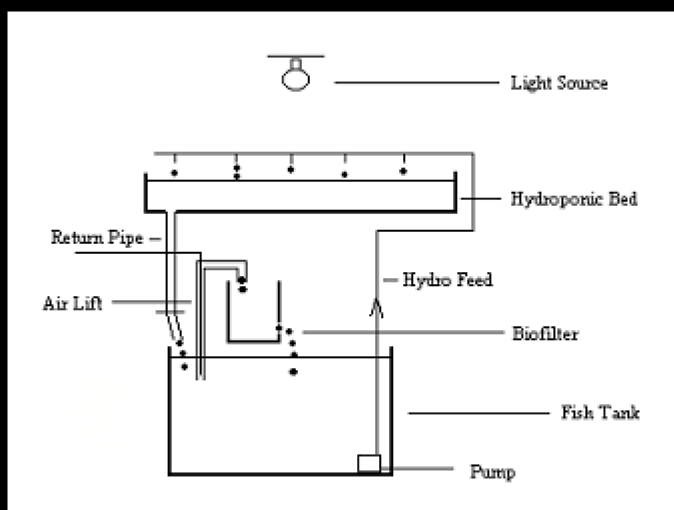


Figure 1: Schematic representation of a single Aquaponic test unit.

Another interesting area to look at is the species of fish used in the aquaponic system. I decided to use Murray Cod, an Australian native fish. Tilapia is not available in Australia and probably never will be due to its extremely high potential for environmental impact. The Murray Cod come from the Murray-Darling basin that straddles about a third of the eastern seaboard of Australia. They are the largest recorded freshwater fish in Australia, with one measured at 183cm (6 ft) long and weighing 113 kg (250 lb)! In recent years it has been discovered that Murray Cod are a very good recirculating aquaculture species due to their fast growth rate, ability to be farmed at high densities (up to 300 kg/Tonne) and superior flesh quality.

Murray Cod are different from Tilapia. Tilapia require approximately 37 % protein in their feed. Murray Cod are presently fed 43 % protein feed and recent research indicates that a 50 % protein content is more ideal. This is a major difference because the whole aquaponic system relationship hinges on the protein content of fish feeds. Nitrate produced in fish waste comes from the protein in the feed. Therefore, the amount of protein in the feed directly relates to the amount of nitrogen-based fish waste and, hence, plant nutrients produced in an aquaponic system. The higher the feed protein content, the more nitrate eventually produced. One (1) kg of Murray Cod, therefore, should support more plants than 1 kg of Tilapia because of the higher protein content of the feed.

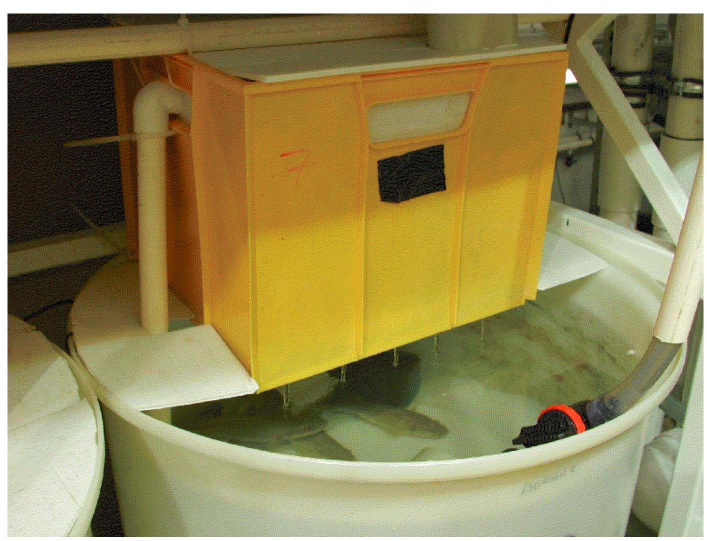
In addition, the food conversion ratio (FCR) of a fish affects the amount of waste produced. A fish with an FCR of 1.0 is more efficient than a fish with an FCR of 2.0; it takes half as much food to get the same weight gain in the first fish (FCR=1.0). If a fish's FCR is low (eg: 1.0), then more of the available nutrient in the food is going into building body mass in the fish, so less nutrient is released by the fish as waste and less plant growth may be supported. So, in the above example, if grown on the same food (with the same protein content), the fish with the lower FCR (1.0) should theoretically produce less nitrate nutrient waste than the fish with a higher FCR. From these examples it can be seen that a number of factors go into the potential amount of nitrate waste produced by the fish and, therefore, the potential number of plants that can be supported by the aquaponic system.

These ramblings lead to the ultimate question with regard to my research…what amount of a plant (for my research: lettuce) can be grown from a known amount of Murray Cod in an aquaponic system? This is, I believe, a very important question for commercial aquaponics. If an aquaponic system is to have as little wastewater discharge as possible and use as little new, make-up water as possible, then the best way to achieve this is to balance the amount of waste produced by the fish with the amount of nutrients used by the plants as closely as possible. If we can exactly balance that relationship between fish and plants, then we should only have to add small amounts of new water to the system to replace the water lost through evapotranspiration from the plants. From these ramblings, musings and the ultimate question above, I came up with a series of questions built around the design of aquaponic systems. If these questions can be answered, the findings may lead to the design of a system that fulfils my wishes, hopes and aspirations.

What are these questions and how have I gone about answering them? As I said, the ultimate question is…how many lettuce plants are required to be grown so that the amount of waste produced by the fish is exactly balanced with the amount of nutrients used by the plants? A number of sub-questions are posed from this single, ultimate question. These sub-questions include… what is the average FCR of Murray Cod fed on 43 % protein feed? How much waste is therefore

Figure 2 (above): Aquaponic test system, showing Aquaponic units consisting of fish tanks (below) and hydroponic gravel beds containing young lettuce seedlings (above).

Figure 3 (below): Fish rearing component of a single Aquaponic test unit, showing fish tank containing fish and submersible water pump, return pipe and valve from hydroponic gravel bed and biofilter (yellow box with airlift feed pipe at left).



produced by the Murray Cod growing at this FCR? How much nutrient does the average lettuce plant use in its growing cycle? Do different hydroponic components have differing nutrient usage in lettuce growth rates or yields? What other factors affect nutrient use by the lettuce? (eg: the buffer used to counter acidification from fish metabolism, the addition of micro-nutrients to the system). Do different flow rates (or pumping rates) affect nutrient availability and, hence, nutrient use and growth to the lettuce?

As you may have worked out from all of this, these sub-questions lead to an ultimate end point directly helping to answer the ultimate question: can a mathematical model be developed that can be used to predict the relationship between lettuce and Murray Cod to achieve a perfect balance? I must admit to you, though, that these are not all the questions that need to be asked to achieve this. Outside physical factors also come into the equation, such as the amount of solar radiation (sunlight) available to the plants and the temperatures of both water and surrounding air, the oxygen to carbon dioxide ratio and others. Science is good in that it allows you to adjust some of these factors so that they may be considered constant, so the worry of them may be bypassed. That is not to say that they don't have an effect. It is just that I only have 3 years (and little money!) to achieve what I want to achieve, so bypassing these factors enables me to cut my work load a bit. I work indoors in an aquaculture lab using metal halide lighting so light levels, temperatures and other factors may be discounted.

Looking at all the sub-questions above, one may ask...how do you answer all those questions? There are basically two ways:

1. You can design and build a large, single system, test it measuring all kinds of parameters, then use the results to attempt to build your mathematical model. This usually requires a lot of time, a lot of space and, most notable to me, a lot of money! It is, however, an excellent way to achieve your end point and can be done in a situation (like a greenhouse) which is very close to reality.
2. You can design a series of small systems (all identical) and use these systems to isolate and test single parameters, then use the results to attempt to build your mathematical model. The number of small systems allows you to test certain parameters or effects against each other using a scientifically acceptable methodology known as "replication." Replication allows you to test your questions, as well as giving you an idea of how accurate your answers are.

I chose the second method as it is usually far cheaper, requires less space and can be achieved in a shorter time. (see Figures 1, 2 & 3 for system design)

So what has been achieved so far? I am close, I hope, to answering the ultimate question through the use of my mathematical model. A few more months work and I believe I will have the workings of something. I can, however, give you some idea of some of the answers to the sub-questions I have posed.

I have an excellent idea of the average FCR for Murray Cod. Interestingly, the FCR changes over the life span of the fish. FCR seems to drop (ie: food conversion becomes more efficient) as the fish get older. It is lucky for us that Murray Cod grow so large. There are two average market sizes for Murray Cod: about 600g (plate size) and 1000g (banquet size). These sizes may be achieved in less than a year and, because Murray Cod grow so large, the sizes are still at the bottom end of its growing range. When I say FCR drops as the fish get bigger, I mean within the range from 100g to 1200g. I am not sure beyond 1200g what happens.

I also have an excellent idea of the amount of nitrate and phosphate waste a known biomass (or weight) of Murray Cod produce within this size range. This information is invaluable as it allows me to balance the amount of lettuce that can be grown from a known amount of fish. The question of how much nutrient does a lettuce plant use is, as I write, in the process of being answered (fingers crossed – there is a lot of finger crossing in science!).

Table 1
Murray Cod wet weight gain, specific growth rate (SGR), food conversion ratio (FCR) and food Consumption; lettuce mean biomass gain and mean yield (g plant^{-1} & kg m^{-2}); and mean net phosphate and nitrate concentrations for Reciprocal Control and Constant flow treatments.

Parameter	Reciprocating Control	Constant Flow
Fish		
Wet Weight[1] (g / replicate)	173.3^{a} ± 15.3	210.0^{a} ± 17.3
SGR[1] (% / replicate / day)	0.78^{a} ± 0.04	0.92^{a} ± 0.05
FCR[1]	1.25^{a} ± 0.06	0.92^{a} ± 0.05
Feed Fed (g / replicate)	215.0	215.0
Lettuce		
Biomass Gain[1] (g / replicate)	2269.0^{a} ± 23.7	2599.6^{b} ± 11.9
Yield[1] (g plant^{-1})	113.45^{a} ± 5.31	129.98^{b} ± 2.65
Yield[1] (kg m^{-2})	4.34^{a} ± 0.20	4.97^{b} ± 0.10
Nutrients		
Phosphate[1] (mg L^{-1})	4.04^{a} ± 0.39	3.87^{a} ± 0.71
Nitrate[1] (mg L^{-1})	13.30^{a} ± 2.05	11.80^{a} ± 1.78

[1]Values are means ± S.E
a, b: values showing the same letter are not significantly different (P>0.05, n=3) (Mann-Whitney)
SGR specific growth rate (% day^{-1}): [(ln final wt. – ln initial wt.)/(time (days))]x100
FCR food conversion ratio: feed fed/(wet weight gain)

Of more interest to all of you out there may be the questions built around the particular efficiencies of different hydroponic components. The aquaponic system I designed is very basic. It consists of a 100 L fish tank, a 20 L biofilter (fed by airlift) and a hydroponic gravel bed (Figures 1, 2 &3). The fish live in the tank and the tank water is constantly biofiltered to convert harmful ammonia to non-harmful nitrate. Independent of this fish system, I have a submersible water pump that pumps water from the fish tank up to the hydroponic bed which sits on shelves above the fish tank. This water pump is timed to turn on and off when required. The water enters the gravel bed, floods it and then returns to the fish tank via a drainpipe. The fish are generally held at 1 kg per tank which is equivalent to 10 kg / 1000 L, a very low stocking density. I can fit approximately 20 lettuce plants in the hydroponic bed and lighting is supplied by metal halide lights (400 W) which are on for ten (10) hours a day.

I started my work using gravel bed hydroponic components. Gravel beds are great for small systems as they act as both solids and biological filter components and, therefore, may replace traditional aquaculture filtering components. An idea that has been around forever in aquaponics is that reciprocal flows (flood and drain flows- the pump is on for a number of minutes in every hour) need to be used for gravel beds. The argument is that reciprocal flows aid aeration of the gravel beds, increase oxygen availability to the plant roots and aid in more uniform nutrient supply. My experiments showed that a constant flow of water to the gravel bed actually works better than a reciprocal flow in terms of plant growth and nutrient removal (Table 1). Subsequent experiments revealed that the best constant flow-pumping rate for my system was 250 LPH. I must stress, however, that this may be particular to my system design.

Surprisingly, I could find little scientific evidence that directly compared different hydroponic components against each other in either aquaponic systems or traditional hydroponics! I therefore compared gravel beds

Table 2
Murray Cod wet weight gain, specific growth rate (SGR), food conversion ratio (FCR) and food Consumption; lettuce mean biomass gain and mean yield (g plant^{-1} & kg m^{-2}); mean net phosphate and nitrate concentrations, mean weights and removal rates for Control, Gravel, Floating and NFT treatments.

Parameter	Control	Gravel	Floating	NFT
Fish				
Wet Weight[1] (g/rep.)	$220.0^a \pm 16.1$	$206.7^a \pm 13.3$	$266.7^a \pm 29.6$	$250.0^a \pm 25.2$
SGR[1] (% /rep./day)	$0.90^a \pm 0.05$	$0.89^a \pm 0.06$	$1.13^a \pm 0.13$	$1.09^a \pm 0.10$
FCR[1]	$1.01^a \pm 0.08$	$1.07^a \pm 0.07$	$0.85^a \pm 0.10$	$0.90^a \pm 0.08$
Feed Fed (g/rep.)	220.0	220.0	220.0	220.0
Lettuce				
Biomass Gain[1] (g/rep.)		$2639.4^k \pm 28.9$	$2338.1^m \pm 14.5$	$2159.0^n \pm 9.8$
Yield[1] (g plant^{-1})[1]		$131.97^k \pm 6.46$	$116.91^m \pm 3.24$	$107.95^n \pm 2.20$
Yield[1] (kg m^{-2})[1]		$5.05^k \pm 0.25$	$4.47^m \pm 0.12$	$4.13^n \pm 0.08$
Nutrients				
Phosphate[1] (mg L^{-1})	$7.15^a \pm 1.03$	$3.42^b \pm 0.11$	$3.47^b \pm 0.94$	$3.91^b \pm 0.37$
Nitrate[1] (mg L^{-1})	$51.23^a \pm 1.58$	$4.63^b \pm 2.85$	$2.60^b \pm 1.84$	$15.70^c \pm 2.57$
Phosphate (g/rep.) [y]	0.80	0.38	0.51	0.40
Nitrate (g/rep.) [y]	5.74	0.52	0.39	1.62
Phosphate removal (%) [y]		52.5	36.3	50.3
Nitrate removal (%) [y]		90.9	93.2	71.8

[1]Values are means ± S.E
k, m, n: values showing the same letter are not significantly different (P>0.05, n=60) (Anova)
a, b, c: values showing the same letter are not significantly different (P>0.05, n=3) (Mann-Whitney)
y: values are calculated from mean final nutrient concentration per unit volume of test system replicate
SGR: specific growth rate (% day^{-1}): [(ln final wt. – ln initial wt.)/(time (days))]x100
FCR: food conversion ratio: feed fed/(wet weight gain)

(with constant flow) to floating rafts (again, with constant flow) to the nutrient film technique (NFT). I compared them in terms of how much plant growth I got and how much nutrient the plants stripped from the system. The results suggested that gravel beds and floating rafts are very similar to each other in terms of plant yield and nutrients stripped by the plants (Table 2). The shock, however, was the NFT! My results suggest that, in terms of plant yield and nutrient stripping, NFT may be as much as 20% less efficient than gravel beds and floating rafts! Why is this? Probably because in gravel bed and raft systems the plant roots are 100% in contact with the water column whereas, in NFT, only up to 50% of the root mass is in contact with the water. It stands to reason that with up to 50% less contact area, plans grown in NFT will grow a bit slower and, therefore, remove a bit less nutrient. Subsequent flow rate experiments using NFT also proved that the flow rate I used in the above comparison had little affect on the final outcome.

The next thing tested was the type of buffer was needed to be added to the system to keep the pH around 7.0. I had read that potassium (K) based buffers are best because plants require potassium and dislike sodium, of which common buffers in a fish-only system, such as Sodium Bicarb, are composed of. The plants did much better with a potassium-based buffer. An aside to this was that I also tested a calcium-based buffer and a combination of the two. The results suggest that a little more emphasis needs to be placed upon getting some amount of calcium into the system. Calcium is essential to plants as it helps them maintain rigidity in their tissues. This means that, for lettuce, when some calcium is added it assists in producing nice crisp plants. On the flip side, you need to be careful with calcium. If you add too much to the system it actually helps lock away phosphates so that they remain in the system but are far less available to the plants and, thus, lower yields are produced. By my reckoning (again I stress this is not backed up by scientific data), a good rule of thumb is to add potassium-based buffer 6 days a week and calcium-based buffer one day a week, which approaches a good balance.

I hope this gives you some idea as to the complexity of the research involved in aquaponics. It always interests me to note that aquaponics really is also about making two independent, complex systems (recirculating fish culture and hydroponic plant production) into one integrated, less complex system. As you can see, this doesn't always make the science less complex.

I hope to ultimately be able to tell Australian commercial aquaponic farmers how to balance their systems for maximum gain (economically and environmentally) but, as you can see, this will probably be a dynamic, scientific task. Not that this worries me, as I love my aquaponics research.

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