AQUAPONICS RESEARCH PROJECT

The relevance of aquaponics to the New Zealand aid programme, particularly in the Pacific

Commissioned Report

Prepared by Hambrey Consulting

for

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1 EXECUTIVE SUMMARY

1. The report is based on a thorough review of the scientific literature on aquaponics; discussions with specialist aquaponics researchers and producers; analysis of web resources; an online survey of aquaponics initiatives; attendance at a technical consultation on aquaponics at Rarotonga (Cook Islands) organised by the Secretariat of the Pacific Community; and visits to operating aquaponics initiatives.

2. Aquaponics may be regarded as the integration of two relatively well established production technologies: recirculating aquaculture systems in which fish tank effluent is treated and cleaned before being returned to the fish tank; and hydroponic (or soil-less) nutrient solution based horticulture systems. Bringing the two together allows for the plants to utilize the waste nutrients produced by the fish. In principle it is very similar to a freshwater aquarium in which both plants and fish are grown.

3. Aquaponic systems come in a wide variety of forms, ranging from a simple fish tank set below a gravel filled vegetable bed (which also serves as a simple biofilter), with water from the fish tank pumped up and through the grow bed; to highly sophisticated systems incorporating multiple fish tanks, solid waste removal systems, aerobic and anaerobic biofilters, intensive aeration systems for both plants and fish, and sophisticated water quality monitoring and backup (i.e. fail-safe) systems.

4. Aquaponic systems are dominated by vegetable production in terms of area and quantity of product. This is biologically determined by the quantity of plant production required to absorb the waste nutrients generated by fish. In some of the more commercial systems, the fish are simply regarded as a source of high quality organic nutrients, rather than as marketable product in their own right.

5. The technology of aquaponics has been with us since the 1960's, but interest has increased rapidly in recent years due to widespread interest in local sustainable food initiatives, and awareness amongst development agencies that aquaponics may allow for the production of both vegetables and fish in water-deficient or soil-deficient zones. The technology is also of particular interest to aquaculture scientists as a possible tool for the reduction/remediation of nutrient waste from intensive aquaculture production. Scientists, educators and community or development NGOs are, furthermore, particularly attracted to a technology that represents a small managed "ecosystem" comprising a highly productive balance of fish, bacteria and plants.

Global experience

6. Aquaponics initiatives can be found throughout the world, from deserts to northern cities to tropical islands. The industry is dominated by technology and training suppliers, consultants, "backyard" systems and community/organic/local food initiatives. There are very few well established commercial systems (i.e. competing profitably in the open market) and most of those that are have been cross-subsidized by other economic activities, at least in the start-up phase. Many initiatives in temperate zones appear to be struggling. High capital, energy and labour costs on the one hand, and lack of flexibility in meeting market demand on the other, along with constraints on pest management, have been the major problems to date.

7. It is notable that those that are commercial or near commercial are located primarily in Hawaii - because it has a relatively stable temperature regime; a long history of demonstration and research; significant constraints on more conventional forms of

horticulture; high food import costs; and significant demand for “sustainable”, organic and other niche food products.

Strengths/advantages of aquaponics

8. **Efficiency of water use.** Aquaponic systems use 10% or less of the water used in conventional soil based horticulture systems. Water use efficiency in hydroponic systems is probably comparable to that of aquaponics, but more variable, depending on the frequency with which nutrient solution is discarded or dumped.

9. **Independence from soil.** These systems can be established in urban or harsh rural environments where land is very limited or of very poor quality. This advantage applies also to hydroponics and recirculating aquaculture systems.

10. **High levels of nutrient utilization**. This is the core rationale for aquaponics and a significant advantage in those countries or locations where nutrient enrichment[1] is a problem (as for example in some Pacific lagoons). The fish and plants in most aquaponic systems capture roughly 70% of the nutrients input in the form of fish feed; and the residual solid waste is relatively easy to manage and may be applied to fruit trees or conventional horticultural crops.

11. Although **hydroponic systems also capture a high proportion of nutrients** most operators dump the system water periodically to prevent the accumulation of salts and pathogens and allow for thorough cleaning and sterilization. In most cases this relatively dilute waste will not be a problem, and may be used for conventional crop irrigation; on a large scale in sensitive locations treatment may be required in an open pond or lagoon. The requirement or otherwise for this will depend on local conditions and regulations.

12. A further possible advantage lies in the complex organic nature of the aquaponic nutrient solution compared with the relatively simple chemical based solutions used in hydroponics. There is some evidence that this has **pro-biotic properties**, promoting nutrient uptake and protecting against some disease. There is also some limited evidence of **improved product flavour and extended shelf life**. Higher levels of anti-oxidants have been observed in aquaponically grown plants. Not surprisingly these benefits will depend on the quality of the nutrients entering the system – and it has been shown for example that higher concentrations of anti-oxidants are related to the quality of the fish food.

13. **Reduced labour & improved working conditions**. Labour inputs to conventional horticulture are hugely varied dependent on the degree of mechanisation and chemical usage. Aquaponic and hydroponic systems usually use raised beds and do not need weeding. Some of those involved say that there is less work, and the work involved is of a higher quality than that required in more conventional systems. The lack of well established specialist commercial aquaponics enterprises makes comparison difficult.

14. **Two for the price of one.** There is a widespread belief in aquaponic circles that growing fish and vegetables together must save money – you get two products for your investment, labour, and other operating costs. The indications are that this assumption is false. Keeping fish in aquaponic systems adds significantly to both capital and operating costs when compared with a hydroponic system, and some producers have explicitly stated that

[1] High levels of nitrogen and/or phosphorus entering natural water bodies can result in algal blooms, oxygen depletion and in extreme cases radically reduced biodiversity

the fish lose money. The cost is regarded as necessary in order to generate complex dissolved organic nutrients, and produce a product which can be sold at an “organic” premium.

Weaknesses/disadvantages

15. It is unfortunate that the essential and desirable characteristic of aquaponics – closely integrated production of plants and fish to maximise nutrient utilization – also introduces significant disadvantages from both production and marketing perspectives.

16. **Compounding of risk.** Intensive aquaculture production may be subject to losses or reduced productivity related to water chemistry, temperature, lack of oxygen, and disease. Intensive horticulture (including hydroponics) may also be subject to losses from system failure (water supply), pests and diseases. Integration of intensive horticulture with intensive aquaculture compounds these risks since problems or failure of one component are likely to reduce performance of the other. Some risks may even be increased – biosecurity (exclusion of pathogens) is a key issue for intensive recirculating aquaculture systems and may be compromised by recirculation through a large outdoor vegetable production facility. Furthermore, the range of management responses (such as pest or disease management) for each component is constrained by the sensitivities of the other, and it may take some time to restore the whole system to optimal performance. These production risks are further compounded by high capital and fixed operating costs. Any break in production will have substantial cost implications.

17. **Constraints on optimisation and economies of scale.** The drive towards efficiency in conventional food production has resulted in both specialisation and intensification. Specialist farmers or fish farmers are able to bring all their skills and effort to bear on optimisation of their production system for a particular product, and achieve economies of scale in sourcing, production and marketing. While the desirability of this may be questioned on many other levels, there is no doubt that existing economic incentives at both local and global levels continue to strongly favour this trend. Integration in aquaponics not only flies in the face of these incentives, but the intimacy of the integration prevents optimisation of each component. Optimal water chemistry and temperature are slightly different for fish and plants in most cases.

18. **Constraints on production and marketing**. Commercial producers adjust their rates of production as far as possible to meet market demand for different products, and according to seasonality of demand. Some hydroponic producers in Rarotonga for example reduce or stop their production when the market is seasonally flooded with conventionally grown vegetables. Maintaining (roughly) a fixed ratio of fish to plant production, and the long delays and high costs related to shutting down and restarting an aquaponic system, significantly constrain flexibility to adjust production in line with demand.

19. **Energy costs.** Most aquaponic systems will require more energy than conventional horticulture or hydroponics systems, primarily related to the oxygen demand of both fish and bacteria, and the corresponding need for intensive aeration as well as pumping.

20. **Management costs and demands.** Routine maintenance, water quality monitoring and management can be demanding, requiring both skills and dedication. Furthermore, in order to cover the relatively high capital and operating costs, production from these systems must be maximised, requiring high levels of organisation and management in production scheduling, and highly effective sales and marketing.

21. **Limited range of suitable fish species.** Tilapia is by far the preferred fish for aquaponic systems, especially in the tropics and sub-tropics. This is because it is extremely easy to breed, adapts well to high density, is tolerant of low oxygen concentrations (and therefore less susceptible to temporary power failure of system blockage) and tolerant of high nutrient concentrations. Flesh quality is also generally good. However, it is non-native to the Pacific region, and introductions of such a robust species in some countries (such as Australia) has had negative impact on native fauna. While such impacts are unlikely to be as severe in biodiversity limited small islands, there may be issues in some countries. Dependence on highly tolerant species also restricts market opportunity.

22. **Nutrient utilization efficiency is not specifically recognised in sustainable food certifications** such as organic, and the apparent advantage of aquaponics and hydroponics over conventional agriculture in this regard cannot be readily translated into a price premium on the open market. Indeed organic certification of soilless cultivation is still not possible for many organic labels.

23. Although aquaponics uses nutrients efficiently, any assessment of sustainability must also take into account the source of nutrients. Unfortunately the most successful aquaponic systems (in terms of system performance and product quality) **use high quality fish feed as the primary nutrient source, with up to 40% protein and often a high proportion of fish meal**. They also focus on plant rather than fish production. The logic of using fish feed as a source of nutrients for vegetable production in the name of sustainability and food security is questionable. A more rational approach from the perspective of global or regional sustainability would be to use nutrient wastes from other intensive food production systems (including agriculture and aquaculture) as inputs to hydroponic systems.

Conclusions

The overall balance

24. Recirculating aquaculture systems, hydroponic systems and (integrated) aquaponic systems all share the advantage of reduced water use per unit production, and are therefore of interest for development in water deficient islands in the Pacific.

25. From a purely *commercial*, or *economic development* perspective, in almost all circumstances, the disadvantages of aquaponics would outweigh the advantages. Integrating recirculating aquaculture with hydroponic plant production increases complexity, compounds risk, compromises system optimisation for either product, restricts management responses – especially in relation to pest, disease and water quality - and constrains marketing. Energy use is relatively high because of the need for both aeration and pumping in most systems. System failure may result in a two month restart and rebalancing period during which time high fixed costs must be covered. Given that most aquaponic systems are dominated by plant production this is a heavy price to pay, and would require a substantial "organic" premium to compensate.

26. From a *sustainability* perspective there are substantial questions related to use of high quality fish feeds as the nutrient source for systems focused primarily on plant production, and energy use is also relatively high. Solar or wind driven systems would usually be required to make them both economically viable and environmentally sustainable. From a *food security* perspective, especially in water constrained islands, it would appear that hydroponics and aquaculture undertaken as independent activities according to local market need would normally be more attractive, although it is possible that if both became successful, the advantages of integration might then be explored.

Some possible applications and development opportunities

27. Notwithstanding this rather negative overall appraisal, there may be opportunities for specific kinds of aquaponics initiatives in some locations, so long as the key features and risks associated with these systems as described above are fully understood at the outset.

28. **Small-medium scale vertically integrated production/restaurant/retail/resort**. In Europe and the US the most successful aquaponics ventures are those where the aquaponic venture is combined with other "visitor attractions" and/or an organic/ local produce shop and/or café or restaurant. The Pacific version of this model might be an aquaponics café/shop in or close to significant urban and tourism centres and/or aquaponics directly linked to a resort, especially on water deficient islands where fresh vegetables are difficult to source. In this case the resort or café fully understands the production limitations and risks, but exploits the intuitive appeal of aquaponic systems. Staff are also likely to be permanently on hand to deal with routine care and maintenance of such systems at limited marginal cost. Again this might be done with either hydroponics or aquaponics but the tourist appeal of the latter is likely to be greater.

29. **Education and social development in small institutions**. In so far as an aquaponic system is a microcosm of a freshwater (potentially marine) ecosystem, and illustrates many of the essential processes of life and "ecosystem services" it serves as an excellent educational and skills development tool. The complexity of management and the requirements for dedicated husbandry and significant planning and organisational skills – while being a disadvantage from a commercial perspective – may be considered an advantage when seeking to strengthen communities, team work, and responsibility. As such, the development of aquaponic systems in schools, communities, prisons, military camps etc. may meet a range of other needs while at the same time generating some healthy locally produced food. Again the rationale and opportunity for this will be greater in water and soil deficient islands. There is however a significant risk that such systems will nonetheless break down once the initial flush of enthusiasm is over, and without a strong commercial incentive to maintain efficient production. The absence of a determined "champion", limited access to high quality cheap fish food, and high costs of electricity are also likely to be a significant constraints on longer term success.

30. **Household scale production** may have some potential in water/soil deficient islands, or where people are sufficiently wealthy that investment in backyard gardening becomes a worthwhile hobby activity in its own right. Relatively simple "2 bucket" backyard designs may be fairly robust and resilient, so long as feed inputs are kept below some basic operating thresholds, and so long as Tilapia (or possibly catfish) are available. The main constraint here will be energy cost and energy/equipment reliability. Operating costs may be reduced through investment in solar panels/wind turbines and batteries, and reliability can be addressed through investment in monitoring systems and backup[2]. In most cases however small scale *hydroponic* systems are likely to serve this need better at least in the first instance. These may be upgraded to aquaponic systems once skills have been developed, and if there is demand for fish and a ready supply of high quality fish feed and seed.

[2] For example backup pumps, aerators, electricity supply

The way forward

31. Aid agencies and NGOs should be extremely cautious about supporting aquaponics initiatives. The focus of development activity should not be on the promotion of aquaponics per se; rather on raising awareness of the range of options available to enable vegetable (and in some cases fish) production in water and soil deficient islands, and facilitation of local initiatives aimed at overcoming these constraints.

32. Where aquaponics appears to be an attractive option, thorough local feasibility studies should be undertaken before investing in any demonstration systems or support programmes. Such assessments should consider carefully whether aquaponics in a particular location will have any real advantages over hydroponics and/or stand-alone aquaculture production systems (or indeed fisheries) as a means of generating high quality food in water and soil deficient islands; and whether the skills, knowledge and dedication are available to sustain viable aquaponics. In any case, given the complexity of the systems it is arguable that aquaculture and/or hydroponic systems should be introduced first, and if successful may be combined with the other component at a later date, if local physical and economic conditions favour such integration.

33. To date, aquaponics has been primarily pursued by aquaculturists through aquaculture/fisheries agents, despite the fact that it is primarily a horticultural activity. There needs to be a rebalancing of effort and support, primarily through agricultural training and extension, but also through joint initiatives of fisheries and agriculture services where appropriate.

34. To date integration of recirculating aquaculture and hydroponics has been promoted as a "good thing", almost as an article of faith. It is essential that in future the disadvantages of integration – at least in the current economic and marketing climate – are also fully understood.

2 INTRODUCTION

Aquaponics is a food production system that combines intensive aquaculture (raising aquatic animals in tanks) with hydroponics (cultivating plants in a nutrient solution). The nutrient rich effluents from the aquaculture component are circulated through the hydroponic component where a proportion of these nutrients are taken up by the plants before the water is returned to the fish tanks.

There is global concern about how future generations will produce more food sustainably. Agriculture has substantial environmental impact on natural resources: the conversion of natural land to agriculture, nutrient leaching and the use of chemicals are all serious issues[3]. In the last 20 years nitrogen use in chemical fertilizers has exceeded by 20 times the nitrogen content in the oceans[4] and brought severe eutrophication to water bodies[5]. Closing the loop between crops and animals is therefore seen as the only way to improve water and nutrient efficiency and reduce wastes. Reducing land use would make a further contribution to sustainability. Aquaponics, by combining fish and vegetable production and maximising land, water and nutrient use efficiency, appears to offer a possible way forward in this regard, and has particular attractions in locations where water is scarce and/or soil is poor, and where there is strong demand for both fish and vegetables.

The popularity of aquaponics has been increasing since the 1990s. The Aquaponics Journal began publication in 1997 and brings together research and applications of aquaponics from around the world. Globally there are hundreds of small scale aquaponics initiatives and several larger semi-commercial operations.

Other than in Hawaii, aquaponics initiative in the Pacific region remains limited. The New Zealand Aid Programme funded a demonstration project in Rarotonga in 2012 which has been operational for approximately 12 months. The Secretariat for the Pacific Community (SPC) has a demonstration site at its campus in Suva which has also been running for 12 months. A small trial is being coordinated by Pacific Wellness Centres in the Marshall Islands. The College of Natural and Applied Sciences of the University of Guam runs a demonstration system as part of the Triton Model Farm for Research and Education. There are also several small backyard systems and school project initiatives scattered throughout the region. In response to significant and growing regional interest in aquaponics, SPC hosted a week-long Aquaponics Expert Consultation at the site of the NZ-funded demonstration project in Rarotonga in September 2013.

Given the rapidly increasing global interest and the potential relevance of aquaponics to water deficient islands in the Pacific, the New Zealand Ministry of Foreign Affairs and Trade decided to commission a thorough review of the nature and potential of aquaponics. The goal of this study is to:

> *Assess relevant international literature and experience to inform Ministry of Foreign Affairs and Trade decision-making about whether and how aquaponics might be relevant to the New Zealand Aid Programme, particularly in the Pacific.*

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[3] Tillman, D., Cassman, K.G., Matson, P.A., Naylor, R. and Polasky, S. 2002. Agricultural sustainability and intensive production practices. Nature 418:671-677

[4] Downing, J.A., Baker, J.L, Diaz, R.J., Prato, T., Rabalais, N.N. and Zimmerman, R.J. 1999. Gulf of Mexico Hypoxia: Land and Sea Interactions Task Force Report No. 134. Council for Agricultural Science and Technology, Ames, IA

[5] National Research Council. 1999. Nature's Numbers: Expanding the National Economic Accounts to Include the Environment. National Academy Press, Washington DC

This report and associated appendices was prepared to meet this goal.

3 ORIGINS AND HISTORY

In practical terms, aquaponics is the integration of *intensive recirculated aquaculture* in tanks with *hydroponic* production of vegetables in nutrient solution. The history of both these technologies is therefore relevant to this analysis.

3.1 Origins of hydroponics

Hydroponics comes from the Greek words *hydro* (water) and *ponos* (work). The growing of plants within a liquid or solid media (organic or inorganic) uses a wide range of dissolved macro and micronutrients, which are supplied in aqueous solution.

Hydroponics has a long history, and was an important element in agricultural systems throughout the world. In China it was reported that "frame fields" for growing water spinach were widespread in ancient times[6]. The raft gardens were made with a frame of bamboo and a layer of soil and supplied leaf vegetables for home consumption[7]. In Mexico and Bangladesh organic matter from plants was used to create rafts for floating agriculture[8]. In Latin America in pre-Hispanic times *Chinampas* were probably the most intensive and productive agricultural system, and were part of a larger integrated agricultural system that supplied food for the local population[9]. In the Chalco zone in the year 1519 the 10,000 hectares under such cultivation were said to supply food for up to 180,000 people[10]. This form of agriculture was mainly carried out in swampy and flooded areas, wherever lack of land constrained more conventional agricultural production[11], or as a primitive example of “urban agriculture” or “roof agriculture” that took advantage of internal resources (sludge and ash) in the hanging gardens of Babylon[12]. Floating agriculture was also developed in Asian countries such as Kashmir (“rádh”)[13], Pulawat atoll in Micronesia (“maa”)[14], Inle Lake in Myanmar, and in the Tonle Sap lake of Cambodia. This type of agriculture is still in use, for example in Myanmar, Bangladesh and Cambodia.

Hydroponics first appears in the scientific literature in the 17th century[15] and has been optimised for commercial operations in the first half of the 20th century. In Western countries, interest in soil-less culture for vegetable production started in 1925 when greenhouse vegetable production encountered chronic problems with soil-borne disease. During World War II hydroponic production was increased to supply the US army with fresh vegetables, and

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[6] Simoons, F.J., 1990. Food in China: A Cultural and Historical Inquiry. CRC Press, Spokane, WA, USA. p 140

[7] Sirr, H.C., 1849 China and the Chinese, their religion, character, customs and manufactures: the evils arising from the opium trade. Vol I pag 69. Stewart and Murray, old Bailey, London, UK

[8] Palagri, P. 2004 Ottimizzazione della nutrizione del basilico in fuori suolo. BSc thesis, Tuscia University, Italy., Parvej,H., 2008 Personal communication. Actionaid! Bangladesh. Dhaka, Bangladesh

[9] Sutton, M.Q. and Anderson, E.N. (2004) Introduction to cultural ecology. Altamira press, Lanham, MD, USA. 352 pp; Adams, R. E.W., (2005) Prehistoric Mesoamerica. University of Oklahoma press, Norman, OK, USA. 544 pp

[10] Adams, 2005 op cit

[11] Palagri, 2004 op cit

[12] Leoni S. 2003 Colture Senza Suolo in Ambiente Mediterraneo. Le Nuove Tecniche per L’orticoltura e la Floricoltura da Serra. 278 p. Edagricole, Bologna, Italy.

[13] Simoons, 1990 op cit

[14] Manner, H.I, 1994 The Taro Islets (Maa) of Puluwat Atoll. Land Use and Agriculture: Science of Pacific Island

[15] Weir, R.G. Cresswell, G.C and Awad, A.S. (1991) Hydroponics – growing plants without soil NSW Agriculture & Fisheries, Orange.

expanded further from the 50's and 60's all around the world[16]. The further development of plastics and greenhouse technology created favourable conditions for the use of soilless production under any climate[17]. Several media were used (sand, sawdust, peat etc.), but in the seventies the invention of the nutrient film technique (NFT) and rockwool as a growing medium led to increased efficiency. More recent advances include the use of fine mist spray of nutritive solution at root level (aeroponics), though adoption has been limited to date[18].

Hydroponics is now a well-established and fully commercial vegetable production system already widely applied in tropical and sub-tropical island nations, including for example The Cook Islands, Fiji, Mauritius, Hawaii, Jamaica and many others.

3.2 Intensive recirculated aquaculture

Although extensive aquaculture, based on the use of naturally available food in ponds, supplemented with household scraps, has been around for thousands of years, intensive aquaculture in which fish are kept at high density in tanks or raceways and fed a high quality food pellet has been with us only since the mid-20th century (although eels were cultured intensively in Japan using a fish based food mash towards the end of the 19th century). As production intensified it was realised that the effluent was high in nutrients and could cause eutrophication and other environmental impacts[19]. Furthermore significant production was only possible where plentiful water was available to prevent build-up of metabolites toxic to fish[20]. A range of wastewater treatment technologies have been developed to reduce the nutrient loading on the environment and/or allow for the recycling of water. These include settling of solids and bio-filtration to remove nitrogen and other nutrients from the water.

However, the costs of water treatment and recirculation are high, and recirculated aquaculture represents a tiny proportion of modern aquaculture production. It is used primarily in hatcheries, where the value of the product (per kg) is relatively high, and the advantages of recirculation in terms of environmental control are significant. It is also used in some countries where freshwater effluent standards are extremely strict (such as Denmark). Elsewhere production in cages in open water, or production in ponds or tanks with some simple effluent treatment (such as settling pond) has proven to be far more cost effective, and if well managed, environmentally sustainable. We are not aware of any fully commercial recirculated aquaculture systems in the Pacific Islands.

[16] Leoni S. 2003 Colture Senza Suolo in Ambiente Mediterraneo. Le Nuove Tecniche per L'orticoltura e la Floricoltura da Serra. 278 p. Edagricole, Bologna, Italy.
[17] Resh H.M.2004 Hydroponic Food Production. A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower. Sixth Edition. 567 p. Newconcept press, Mahwah, NJ, USA.
[18] Hassall & Associates, 2001. Hydroponics as an Agricultural Production System. RIRDC Publication No 01/141 RIRDC Project No HAS-9A
[19] E.g. Piedrahita, R.H., 2003. Reducing the potential environmental impact of tank aquaculture effluents through intensification and recirculation. Aquaculture 226:35–44; Verdegem, M.C.J., Bosma, R.H. and Verreth, J.A.J. 2006. Reducing water use for animal production through aquaculture. Water Resources Development 22:101–113; Chamberlaine, G., Rosenthal, H., 1995. Aquaculture in the next century: opportunities for growth, challenges for stability. World Aquac. Soc. Mag. 26 (1), 21–25; Costa-Pierce, B.A., 1996. Environmental impact of nutrients from aquaculture: towards the evolution of sustainable aquaculture systems. In: Baird, J.D., Beveridge, M.C.M., Kelly, L.A., Muir, J.F. (Eds.), Aquaculture and Water Resource Management, Blackwell, UK, pp. 81– 109
[20] Barnabé, G., 1990 Aquaculture, (II volume) 2nd edition. Ellis Horwood Limited, Chichester, England pp 1104; Diana, J.S.,Szyper, J.P, Batterson, T.R., Boyd, C.E., Pedrahita, R.H. 1997. Water quality in ponds. In: Egna, H.S, Boyd, C.E. (eds) Dynamics of pond aquaculture. CRC press, Boca Raton, New York. 437 pp

Where recirculation or water treatment is desirable or required, plants are rarely used for final water treatment because the efficiency of modern bio-filtration is usually more than adequate to meet environmental standards.

3.3 Aquaponics

Aquaponics, in which an aquaculture system is integrated with a hydroponic system, also has an ancient history. Plants have been grown using fish farm wastes either directly or indirectly in China and SE Asia for hundreds if not thousands of years.

While Western economies have no such ancient tradition, interest in aquaponics has been strong since the 1960s, with early work for example in the US at Woods Hole Oceanographic Institute[21]. Since that time there have been many major research projects and programmes throughout the developed and developing world, reinforced by the growing awareness of the need to reduce the impact of nutrient wastes on the environment while at the same time increasing the efficiency of nutrient use in food production. The heightened interest in aquaponics is reflected in the existence of the dedicated Aquaponics Journal which was established in 1997.

Globally there are now hundreds of small scale aquaponic initiatives and several larger scale commercial or near commercial enterprises – the latter mainly in the USA and in particular Hawaii.

In parallel with research on aquaponics there has also been substantial research on integrated multi-trophic aquaculture (IMTA) in which fish and plants are grown in more open systems[22]. The classic examples here are of growing caged salmon in close association with mussel and seaweed cultivation. Despite substantial pilot scale research for well over a decade however, these systems have not been adopted on a significant commercial scale, mainly because of the large quantity and low value of seaweed produced, reduced water circulation around the fish cages, and a range of other management issues.

It is also notable that in parallel with the growing interest in integrated food production systems in the research community, there has been a strong tendency toward reduced "integration" in the ancient heartland of integrated agriculture-aquaculture systems – China - where the economic environment, as in most Western countries, has favoured increased specialization and intensification.

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[21] Ryther, J.H. Goldman, J.C., Gifford, C. E. Huguenin, J. E. Wing, A. S. Clarner, J.P., Lavergne, Williams, D. Lapointe. B. E. 1975. Physical models of integrated waste recycling- marine polyculture systems Aquaculture Volume 5, Issue 2, March 1975

[22] *see for example* Neori, A. Krom, M.D., Ellner, S.P., Boyd, C.E., Popper, D., Rabinovistch, R., Davidson, P.J., Dvir, O., Zuber, D., Ucko, M., Angel., D and Gordin, H. 1996. Seaweed biofilters as regulators of water quality in integrated fish-seaweed culture units. Aquaculture 141:183–199; Neori, A. Ragg, N.L.C. and Shpigel, M. 1998. The integrated culture of seaweed, abalone, fish and clams in modular intensive land-based systems: II. Performance and nitrogen partitioning within an abalone (Haliotis tuberculata) and macroalgae culture system. Aquacultural Engineering 17(4):215–239 ; Neori, A., Chopin, T., Troell, M., Buschmann, A.H., Kraemer, G.p. Halling, C., Shpigel, M and Yarish, C. 2004. Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. Aquaculture 231: 361–391

4 THE TECHNOLOGY

Aquaponic systems integrate recirculated aquaculture systems (RAS) and hydroponics. It is therefore worth reviewing the technology associated with both these subcomponents.

4.1 Hydroponic systems

Hydroponic systems and their operation are described in detail by Resh (2013[23]). There are three main types of hydroponic plant growing system that are also suitable as the plant growing component in aquaponic systems:

Nutrient film technique (NFT) (Figure 3) – a thin layer of nutrient rich water flows along a tube or closed gutter into which holes are cut and plants are placed, usually in small media filled plastic mesh pots. The upper part of the roots remain in the air while the lower part grow vigorously in the well aerated water.

Deep water or floating raft method (Figure 5) in which nutrient rich water is introduced to grow-tanks of 20-30cm depth, on the surface of which plants are grown through holes in polystyrene rafts. The water is vigorously aerated to maximise nutrient uptake.

Media based systems (Figure 6), where the plants grow in a medium such as gravel, clay balls, vermiculite, cinders etc. These beds may be “trickle fed” nutrient solution, or subject to periodic flooding and draining (“ebb and flow”) to maximise exposure to both air and nutrients. The media beds also function as biofilters.

Figure 1: Nutrient tanks and injection system for hydroponics

These systems (and their variants) may be set up inside buildings or greenhouses, or in the open – either with no protection or partially covered with shade netting, polyethylene or plastic roofing. Nutrients are typically supplied from three stock tanks (Figure 1) using an automated dosing system to maintain nutrients at optimal concentrations for the plants. Nutrients can be managed within closed or open (flow-through) systems[24]. Flow-through systems make the management of nutrients easier but raise concerns over water use and pollution.

4.1.1 Nutrient Film Technique (NFT)

This is the system used most widely in commercial hydroponics businesses throughout the world. A thin layer of nutrient rich water flows from a reservoir tank through slightly inclined custom built troughs and returns directly, or indirectly via a sump tank, to the reservoir tank. Troughs vary in size, but are commonly 10-15cm wide and 5-6cm deep, have a slope of 1% and are

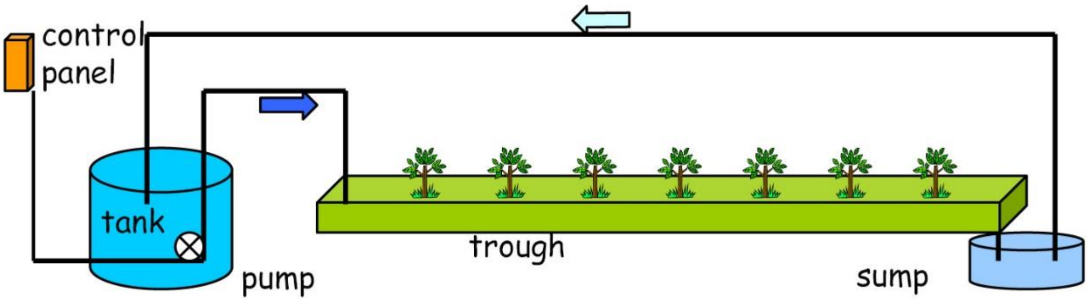
[23] Resh, H.M. 2013. Hydroponic Food Production. A definitive guidebook for the advanced home gardener and commercial hydroponic grower. Seventh Edition. CRC Press
[24] Tesi R., 2002 Colture Fuori Suolo in Orticoltura e Frutticultura. 112 p. Edagricole, Bologna, Italy

no longer than 20-30m long to avoid excessive oxygen depletion, unless aeration is supplied[25]. Nutrient rich water is typically pumped in cycles of 20-30 min with breaks of 4-5 minutes during day, while during the night flow is stopped[26]. This strategy allows roots to get oxygen from liquid media and from the air[27].

To date these systems have been rather little used in aquaponics, perhaps because of the space required (minimum economic length of the growing channels) and the probable problem of build-up of bacterial slime and organic matter in the channels and roots, impeding flow and efficiency.

Figure 2 : Photo of commercial NFT system

Figure 3: Nutrient film technique system

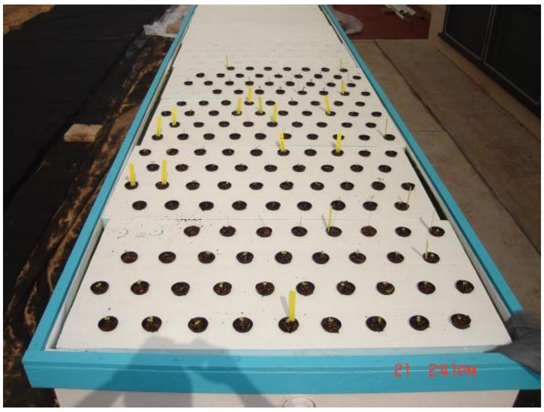


[25] Leoni S. 2003 Colture Senza Suolo in Ambiente Mediterraneo. Le Nuove Tecniche per L'orticoltura e la Floricoltura da Serra. 278 p. Edagricole, Bologna, Italy.
[26] In practice these cycles vary tremendously between growers, some for example operating a 4min on 4 min off cycle for example.
[27] Leoni 2003 op cit

4.1.2 Floating raft system.

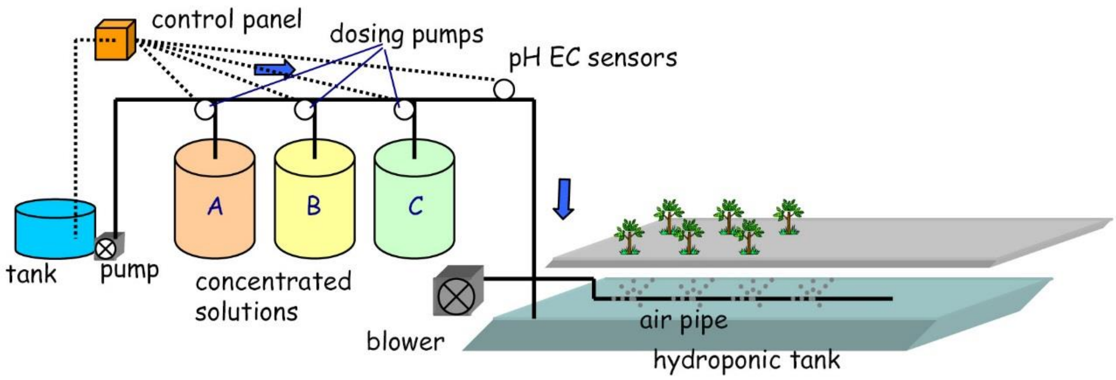
Rafts are usually made from polystyrene with holes for seedlings/pots set around 13cm apart. These float in, or are set slightly above water which flows through troughs or growing tanks usually around 8-10 cm deep and 0.6-1.5m wide (Figure 4). These tanks may be made from any non-toxic plastic or liner such as low density polyethylene (LDPE). Water in the growing tanks is kept oxygenated with air-stones which enhance nutrient uptake by roots as well as providing oxygen for the nitrifying bacteria which convert ammonia and nitrite to nitrate in aquaponic systems.

Figure 4: Polystyrene raft with pots and seedlings (courtesy Larry Yonashiro)



This system has been widely used for leaf vegetables, culinary herbs and radish[28] and is popular amongst aquaponics growers.

Figure 5: Floating raft system



4.1.3 Media or substrate based systems.

Plants are grown in a bed, bag or pot of suitable substrate (Figure 6). A wide range of media are available: organic (straw, bark, seaweed, sawdust and peat), mineral (sand, gravel, perlite, ceramic balls, red/black cinder and rock wool) and synthetic (expanded clay ball; polystyrene, polyurethane). Nutrients are delivered by means of micro-irrigation or sub-irrigation within troughs, or by means an ebb and flow (periodic flood) cycle. The periodic draining of the bed keeps the plant roots well aerated promoting rapid nutrient uptake, and also favours nitrification (conversion of ammonia from the fish tanks to nitrate) when used in aquaponic systems. Ebb and flow can be controlled by a siphon valve or a timer.

These systems are popular with aquaponic producers partly because they can work effectively even on a very small scale, and the media bed doubles up as a bio-filter and solids remover.

[28] Leoni, 2003 op cit

Figure 6: Media based system

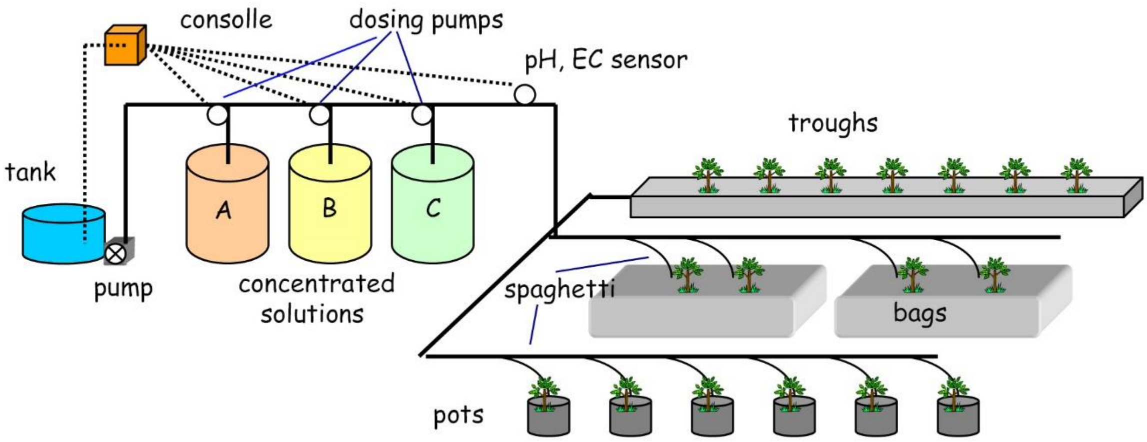
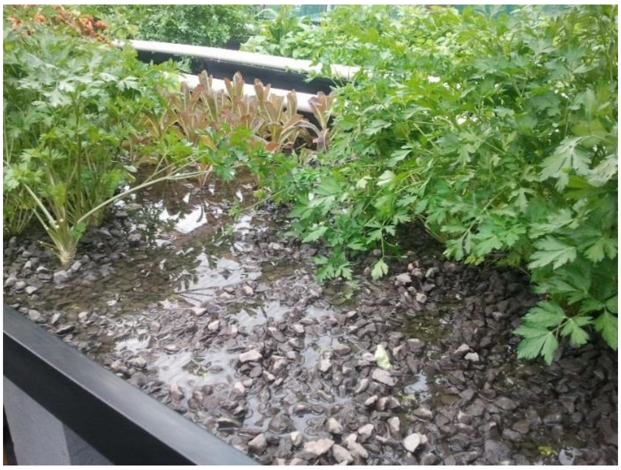


Figure 7: Media based (gravel) "ebb and flow" or "flood cycle" system



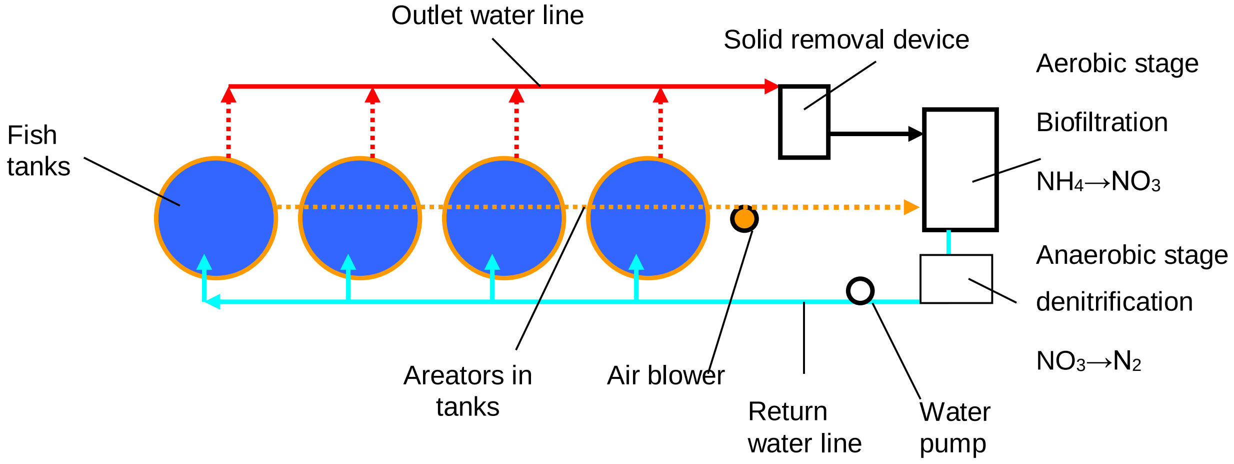
4.2 Recirculated aquaculture systems (RAS)

As noted above, aquaponics was originally developed as an option for enhanced waste treatment in recirculated aquaculture systems (RAS), in which waste water is continuously recycled and returned back to fish after a bio-filtration stage[29].

A typical recirculated aquaculture system is shown in Figure 8.

[29] See for example Rakocy, J.E., Hargreaves, J.A., 1993. Integration of vegetable hydroponics with fish culture: a review. In: J.-K. Wang, Ed. Techniques for Modern Aquaculture. American Society of Agricultural Engineers, St. Joseph, MI, pp. 112–136.; Lennard, W.A. and Leonard, B.V. 2004. A comparison of reciprocating flow versus constant flow in an integrated, gravel bed, aquaponic test system. Aquaculture International 12:539–553; Goulden M. (2005) Production of a Variety of Plant Species in a Gravel Bed Aquaponic Test System with Murray Cod (Maccullochella peeli peeli). MSc thesis. Institute of Aquaculture Stirling University, Stirling, Scotland; Singh S., 1996. A Computer Simulation Model for Wastewater Management in an Integrated (Fish Production-Hydroponics) System. PhD dissertation. Virginia Polytechnic Institute and State University. Blacksburg, VI, USA

Figure 8: Typical components of a recirculated aquaculture system



Water treatment prior to recirculating to the fish includes:

- Mechanical waste removal (uneaten feed, fish solids, dead fish);
- Aerobic bio-filtration in which aerobic bacteria convert ammonia into non-toxic nitrate (nitrification);
- Anaerobic bio-filtration in which anaerobic bacteria convert nitrate in water to free nitrogen gas (de-nitrification) which is released to the atmosphere.

RAS uses little water, and a substantial proportion of nutrient waste is ultimately converted to nitrogen gas in the de-nitrification process[30]. However, these systems produce a significant quantity of nutrient rich solids (faeces and waste food) which are collected in the settling tank, as well as bacterial/organic sludge which is periodically removed from the bio-filters.

4.3 Aquaponic systems

4.3.1 Basic characteristics and components

In aquaponics the anaerobic (de-nitrification) filter used in RAS is largely replaced with a hydroponic plant production system. If this is a media based hydroponic system it will also serve as an aerobic biofilter, converting ammonia to nitrate. From the plant production perspective, the nutrient injection system normally used in hydroponics is replaced with a fish production/nutrient waste generation system.

Part of the nitrogen excreted by the fish is thus taken up by the plants rather than being released to the atmosphere, and the plants also remove a wide range of other nutrients from the water including phosphorus. Of total nitrogen input into the system as feed, up to 30% may be captured as fish flesh, and 40% or more captured as plant biomass. The balance is lost as

[30] Verdegem, M.C.J., Bosma, R.H. and Verreth, J.A.J. 2006. Reducing water use for animal production through aquaculture. Water Resources Development 22:101–113

nitrogen gas or as solids, which may be used to fertilize a garden[31]. Higher levels of nutrient capture may be possible with additional separate biofiltration[32]. Furthermore, the complex mix of nitrifying bacteria, rhizobacteria, fungi, and micro plankton in the recirculated water appears to benefit the plants due to both positive interactions at root level, and the higher resilience of the system against some plant pathogens[33] .

It should be emphasised that most aquaponic systems – and certainly those that seek to maximise the use of waste nutrients produced by the fish – are dominated by the plant production (hydroponic) component in terms of both area and production. This is quite simply because you need an awful lot of vegetables to absorb the waste nutrients generated by intensively grown fish.

Aquaponic systems may include the following components, though not all are required if the system is to be run at low intensity and primarily for plant production.

- Sump
- Fish tank
- Settling tank or clarifier
- Physical filter (which may also serve as an anaerobic, denitrifying filter)
- Aerobic bio-filter
- Degassing unit
- Grow-beds or tanks
- Blower/aerator/diffuser
- Pump

Two extreme examples of aquaponic systems are shown in figures 9 and 10. A wide number of variants on these basic themes are available and recommended by different manufacturers but will not be described in detail here. A web search will reveal a range of off-the-shelf systems.

Fish tanks are typically round in shape to improve water flow and prevent “dead” areas where solids can build up. In almost all systems aeration is provided to optimise conditions for fish (and plant) growth, allow for high stocking densities, reduce the risks associated with water supply failure (e.g. blockage or pump failure), and facilitate nitrification. Stocking densities can be very high dependent on the species, temperature and level/efficiency of aeration. For example Nile Tilapia (*Oreochromis niloticus*) can be stocked at up to 60-70 kg/m^3. Carp could also be stocked at similar densities given adequate aeration. In temperate countries trout would thrive at considerably lower densities.

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[31] Fox, B et al . 2013. Toward Lower-Cost, More Reliable, Pacific-Friendly Aquaponics Systems. Presentation to the Expert Consultation: Aquaponics for the Pacific Islands Region: Review of Opportunities and Constraints Secretariat of the Pacific Community Aquaculture. September 23rd-27th, 2013, Rarotonga, Cook Islands

[32] Lennard “Fact sheet “fish:plant ratios www.aquaponicsolutions.com.au

[33] Savidov, N., 2005. Evaluation and development of aquaponics production and product market capabilities in Alberta. Phase II. Final Report - Project #2004-67905621; Pantanella, E., Cardarelli, M., Colla, G., Rea, E., Marcucci, A. 2012. Aquaponics vs Hydroponics: Production and Quality of Lettuce Crop. Acta Hort. 927:887-893

Figure 9: Simple small-scale aquaponic System (courtesy Cook Islands Aquaponics Pilot Project)

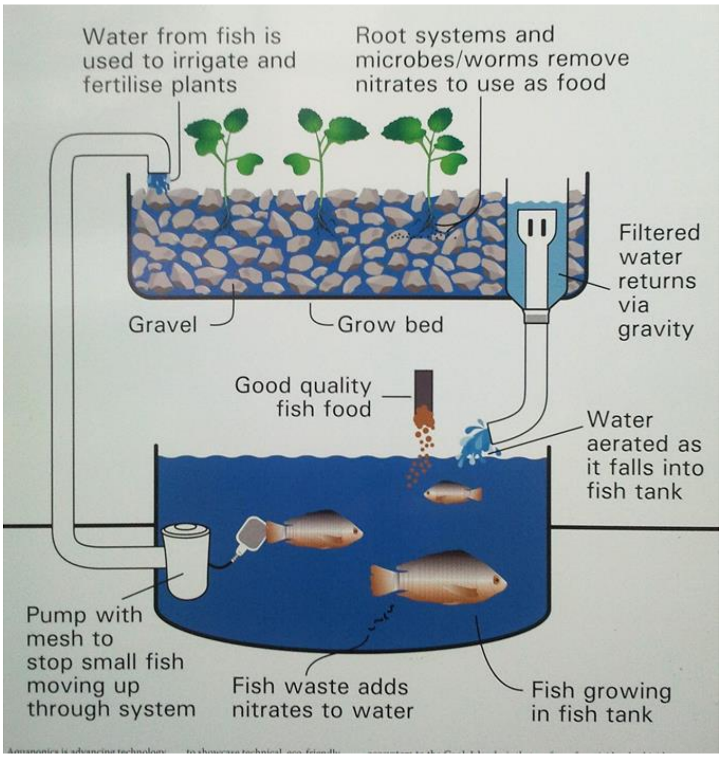

Figure 10: More complex aquaponic system (plan view)

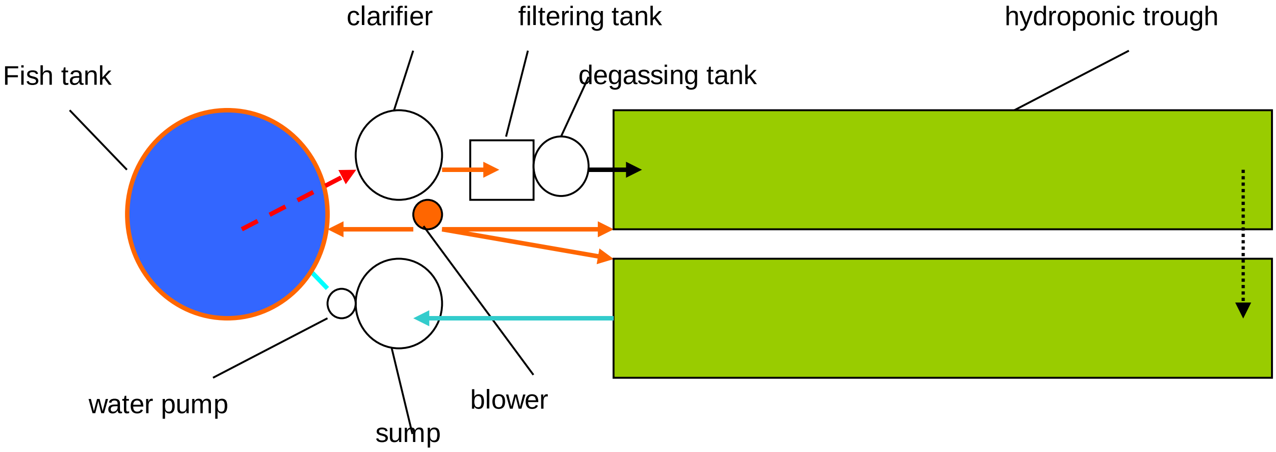

Figure 11: Fish tank with Tilapia in small scale aquaponic system

Solid removal units are diverse ranging from simple conical settling tanks or clarifiers to more sophisticated, swirl separators, radial flow and drum filters. Removal performance may be 40-60% in these and similar systems, although much depends on the size and species of fish and nature of the feed. Up to 78% separation has been achieved with more sophisticated systems such as radial flow separator[34]. Whatever system is used, suspended solids need to be removed otherwise they will clog plant roots and accumulate in "dead spots" throughout the system. These may become anaerobic, releasing toxic hydrogen sulphide to the detriment of both plants and fish.

A variety of **physical and/or biological filters** may be used to further reduce suspended solids and in some cases to contribute to bio-filtration. In the system developed by University of the Virgin Islands (UVI system) "filtering tanks" are filled with orchard nets, which serve as both physical filter and bio-filter. Most of the remaining suspended solids settle on the mesh and mineralize or are digested by bacteria (nitrification). Anaerobic conditions may occur wherever thick layers of solids accumulate, and this may in turn facilitate de-nitrification[35].

In systems designed to produce significant quantities of fish, more efficient **dedicated aerobic and anaerobic bio-filters** may be installed. Some of the nitrate will be removed as gaseous nitrogen from the anaerobic filter, and this will allow for a higher ratio of fish to plants.

In highly stocked systems intensively aerated **degassing tanks** may be necessary to eliminate hydrogen sulphide and carbon dioxide after the anaerobic phase. The former gas is extremely toxic for fish and must be removed efficiently.

In most systems (and certainly those without dedicated stand-alone anaerobic biofilters) the **plant troughs or growing beds** are the dominant part of the system, taking up most of the space and labour, and generating most production. **In floating raft and nutrient film systems**, nitrifying bacteria will grow on every surface of the system as well as in the water column; and in floating raft systems additional removal/mineralisation of suspended solids takes place in the plant tanks[36]. In **media** based systems, the plant beds themselves function also as biofilters, negating the need for stand-alone biofilters, except where a high ratio of fish to plants is required.

A **blower or air pump** is required to keep oxygen levels as high as possible for the health and growth of both fish and plants. Aeration is also desirable backup for fish in case of pump or

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[34] Davidson, J. and Summerfelt, S.T. 2005. Solids removal from a coldwater recirculating system—comparison of a swirl separator and a radial-flow settler. Aquacultural Engineering 33:47–61
[35] Rakocy, 2008, personal communication
[36] Rakocy, J.E., 2007 Aquaponics, integrating fish and plant culture. In: Simmons, T.B., Ebeling, J.M. 2007. Recirculating aquaculture. Cayuga aqua ventures, Ithaca, NY - USA pp 767- 826

pipe system failure. In the simplest of systems as illustrated in figure 9, it may be possible to do without aeration, but this will reduce system performance and increase risk of fish loss.

Aeration needs are much higher in floating raft systems where plant grow tanks are intensively aerated to increase nutrient uptake by plants and to facilitate de-nitrification. In both media bed and NFT systems aeration of the water and roots takes place passively, as the water flows through the air in a thin layer or the roots are exposed to air on a cyclical basis.

The sump is a collecting or storage tank from which water is pumped to the fish tanks, and to which water from the plant beds drains.

4.3.2 State of the art

There is an almost infinite variety of aquaponic systems currently in operation. They vary in terms of:

- Plant growing system (NTF; raft; media based)
- Species of fish and plant
- Enclosure (building and artificial light; greenhouse; net house; simple open cover; back yard)
- Level of investment (number of components in system; sophistication of components; backup; monitoring/automation)
- Type of enterprise

The floating raft systems used worldwide tend to follow the University of the Virgin Island model, although different materials are used according to their availability: fibreglass, metal grates with polyethylene liners, concrete with liners, wood with liners.

There have been some technical advances in recent years on fish waste treatment and system integration. In Alberta - Canada a “5th generation aquaponics” aims to produce zero-waste through complete mineralization of fish solids (Savidov, 2012) and this is also the objective of some of the systems being developed by Wilson Lennard in Australia. Integration with biofloc systems (production of bacterial colonies to feed the fish) or algal production has also been suggested as an alternative or additional way to get rid of ammonia in aquaculture tanks and reduce the plant:fish ratio.[37]

4.4 Strengths and weaknesses of alternative aquaponic technologies

A summary analysis of the strengths and weaknesses of alternative hydroponic and aquaponic production technologies is presented in Table 1. The relative advantages of the various systems are the subject of much debate and promotion, and there is rather little purely independent appraisal, the majority of comparisons being put forward by proponents of a particular technology. Some general points, of particular relevance to potential development in the Pacific, are as follows.

For **small scale “household” systems** there are some significant advantages in using just two primary units – a fish tank set below one or more media based plant growing beds. This

[37] www.bofish.org.

is because the media bed also serves as the bio-filter[38], and aeration is largely passive, eliminating the need for intensive continuous aeration. In most cases therefore these will be cheaper to operate, and at relatively low production intensity are likely to be more stable that floating raft systems. However, while there may be no *requirement* for continuous aeration, this may nonetheless be *desirable* to maintain optimal conditions in the fish tank (especially if the grow bed is based on ebb and flow system), and as a backup in case of pump failure or system blockage/malfunction.

These simple systems are however unlikely to function well as intensity is increased and efficient production of fish becomes a significant objective. The increased waste loading (especially solid waste) on the grow-bed/filter is likely to result in accumulation of organic matter, channelling, reduced aeration, and the development of locally anaerobic conditions. While this may be beneficial in some respects (increasing de-nitrification) it is likely to reduce plant yield, reduce oxygen concentration in the water, and possibly generate toxic gases.

For **larger scale systems** there is little consensus, but the following are important considerations. Floating raft systems are very convenient in terms of production organisation and scheduling, and handling. The rafts are light, can be moved around easily, and root health and growth can be readily assessed. System cleaning is also simple, especially if tanks are modularised. On the other hand, if the system is to be run at a high rate of productivity, and especially if a significant quantity of fish (relative to plants) are to be produced, highly efficient settling and separate bio-filters will be required. Furthermore the range of plants that can be grown well is probably more limited in floating raft compared with media based systems.

NFT systems have not been widely used in aquaponic systems, but this probably relates to scale (there is a minimum commercial length for the channels/gutters). It may also relate to the increased likelihood of bacterial and solids build up in aquaponic compared with hydroponic systems, and this may clog and disrupt functioning of NFT systems.

[38] Lennard, W.A. and Leonard, B.V. 2004. A comparison of reciprocating flow versus constant flow in an integrated, gravel bed, aquaponic test system. Aquaculture International 12:539–553 (outlined the enhanced nitrification obtainable from gravel systems and the potential buffering capacity of gravel).

Table 1: Strength and weaknesses of alternative plant growing technologies for use in aquaponic systems

Strengths	Weaknesses
Nutrient film technique	
• Simple • Planting density adjustment easy • Passive aeration means lower aeration cost • Nutrient dose can be adjusted real-time • Easy cleaning sterilization and management (modular) • More passive warming of water in temperate greenhouse	• Vulnerable to pump failure/ loss of water flow • Low water volume means less stable – less buffering (nutrients; toxins) • Low water volume and thin film implies susceptibility to overheating in tropical regions, overcooling in temperate regions and large diurnal temperature variation
Floating raft system	
• Can withstand temporary pump failure better than NFT or media based • Larger water volume relative to fish and plant stock increase systems' buffering capacity against ammonia • Larger volume of water equates to a significant reserve of nutrients in the water column, even when fish are temporarily removed. • Insulated system with high water volume and thermal mass reduces temperature fluctuation • Rafts provide some biofiltration surface; easy moving; easy production management; easy maintenance.	• Mosquito breeding. (However, these may be controlled using guppies or mosquito fish). • Escaped fish may graze roots. • Unsuitable for root and fruit and some other plants • High water volume implies higher cost for nutrient supplements such as iron, in order to maintain optimal concentration. • Insulation may reduce desirable warming from sunshine in temperate regions
Media based	
• Suitable for a greater range of plants including root crops • Substrate doubles as biofilter (nitrification) – allowing for technical simplicity and/or a higher ratio of fish:plants than raft systems • Probably less pumping head loss compared with systems that incorporate separate biofilter • Substrate may also perform buffering (increase pH) function • Ebb and flow or trickle allows for passive aeration of media and roots and lower energy costs • Trickle or sub-irrigation systems may be more efficient regarding use of nutrient supplements • Broadcast sowing on the media surface is possible, avoiding the need for a separate nursery/seedling installation	• Higher risk to plants in the event of pump failure • Accumulation of organic matter in substrate – leading to channelling and anaerobic conditions (may be tackled using worms) • Imperfect exposure to nutrient solution • Less convenient for harvesting/production scheduling • Direct costs and indirect costs associated with media (e.g. due to weight, handling) • Abrasion of stems in outdoor/windy conditions

5 FISH AND PLANT SPECIES

5.1.1 Plants

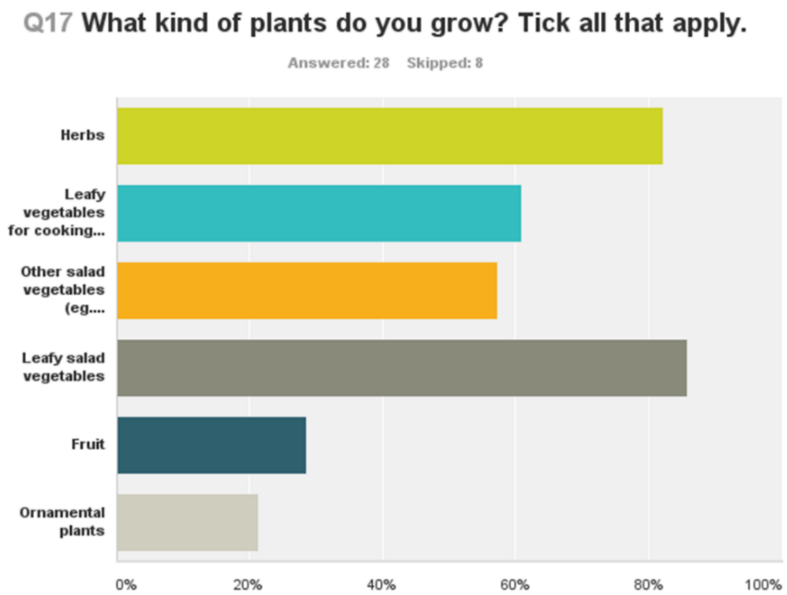
By far the most popular vegetable to grow in aquaponic systems are leafy vegetables and herbs – especially lettuce and basil. These systems are generally less suitable for fruit vegetables because of the longer production cycle and preference for different nutrient ratios. However many species can be grown, especially in media based systems. Some of the more commonly grown include:

- Lettuce
- Basil
- Coriander
- Spring onion
- Bok/Pak Choy
- Chiso
- Fruit vegetables such as tomato, cucumber
- Beets
- Okra
- Taro
- Blueberries

These plants differ in terms of their nutrient needs and nutrient uptake. Fruit vegetables typically have higher nutrient demand and may need different nutrient levels at different stages of growth. They are therefore more difficult to grow successfully in aquaponic systems. Basil and Pak Choy have a higher nitrogen content than (for example) lettuce or coriander, and the balance between fish feeding and plant density may need to be adjusted accordingly.

Figure 12 illustrates the relative popularity of different plant species grown by respondents to our on-line survey.

Figure 12: Plants grown by survey respondents



5.1.2 Fish

Although a wide variety of fish can be grown at high density in tanks in recirculated aquaculture or aquaponic systems, Tilapia (usually *Oreochromis niloticus*) is by far the preferred species for tropical and sub-tropical situations. This is because it is very easy to breed, tolerates low Dissolved Oxygen (DO) levels (0.2 ppm); high Total Nitrate levels (>400 ppm); high Total Ammonia Nitrogen levels (>90 ppm @ pH 6.0) and low pH levels (< 5.0). However it should be understood that for optimal growth and health this species, like most others, prefers DO >6ppm; pH>6; and low ammonia and nitrite levels.

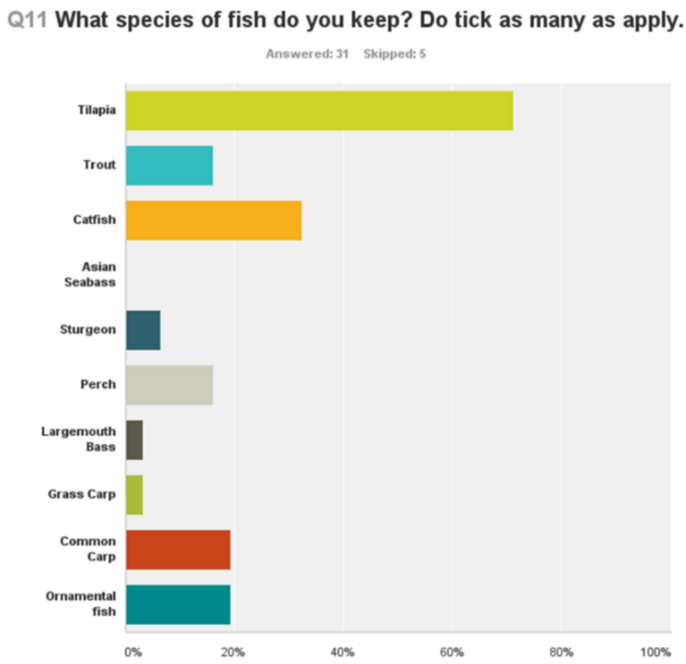
Despite its advantages Tilapia may be a problem in some systems. It will breed very readily even in dense tank culture, and fry may spread to all parts of the recirculation system. They may disrupt the operation of settling tanks or nibble roots in floating raft culture systems. Breeding will also reduce fish production rate/quality.

Many other species have been used in aquaponic systems. Catfish (e.g. *Clarias gariepinus*) also have the advantage of being tolerant of low oxygen and high nutrient contents, and common carp (*Cyprinus carpio*) is a generally robust fish that can be cultured at high density and at slightly lower temperatures. Ornamental fish may also be reared, but many of these prefer high water quality (although goldfish are relatively tough). Trout do well in cold climates, but vegetable growth is likely to be poor at the temperatures preferred by this species (11-17^{o}C). Other species that have been cultured include Murray cod (*Maccullochella peeli peeli*, Mitchell), Asian Barramundi (*Lates calcarifer*), mullet, perch, largemouth bass, bester sturgeon and grass carp.

Grass carp have been suggested as a means of increasing sustainability, since these can be fed grass and waste vegetable matter rather than high protein diet. However, the market is generally poor for this bony and rather tasteless fish, and – as we discuss below - the performance of the vegetable production is highly dependent on the quality of fish feed. Grass is unlikely to be adequate as the ultimate source of nutrients.

The main species kept by survey respondents are summarised in Figure 13.

Figure 13: Fish species used by survey respondents



A more complete list of fish and plant species used in aquaponics is presented in Annex 2

6 SYSTEM MANAGEMENT

6.1 General considerations

The management demands of an aquaponic system depend very much on the extent to which it is a commercial operation. A simple system using fish at relatively low density, coupled with a gravel grow-bed doubling as a bio-filter will produce some plants each month and a few decent sized fish a year. It would be relatively undemanding in terms of management, but the real (especially the energy) cost of the fish and vegetables actually used would be high. Such a system can only really work as a hobby.

At the other extreme, a system intended to run commercially and sell product direct to significant customers (resorts, large restaurants or chains; large scale specialist organic/local food retailer) will need substantial management input including careful monitoring of water chemistry, rigorous production scheduling of both fish and plants, efficient marketing, and effective pest and disease control.

6.2 Managing water chemistry and nutrient availability

The growth and health of both fish and plants depends on water chemistry, which in turn depends on the quality of the feed, the stock of fish, the functioning of settling tanks, biofilters, growbeds, and aeration devices, and build-up of organic material and associated bacteria anywhere in the system.

6.2.1 Conditioning

Stability of chemical composition takes some time (6-9 weeks) to establish depending on temperature and a range of other factors. Prior to that time the stock of both fish and plants must be increased gradually so as not to generate excessive concentrations of ammonia (particularly dangerous to fish at high pH) or more critically nitrite, which is acutely toxic to fish. Disruption of the balance between fish, filters and plants at any time may also result in **ammonia or nitrite "spikes"** that could be fatal to the fish and will certainly reduce performance and increase risk of disease. Such disruption may arise from a significant change in plant or fish biomass (e.g. as a result of harvesting or disease); a significant change in feed input; a change in filter functioning as a result of sloughing of accumulated bacteria/organic matter; cleaning of the system; or a sudden change in pH (for example as a result of inaccurate base addition as discussed below).

These problems are unlikely to be serious unless the system is stocked close to its limits, but any operator must understand these issues and be able to respond rapidly – e.g. by partial water change; restocking; or cessation of feeding.

6.2.2 pH and nitrogen:potassium ratio

Acidity or pH management is also necessary in aquaponic systems, because the pH will steadily decline as a result of the nitrification process, which increases H^+ and $NO3^-$ ions in the system. This can be countered by addition of a long-term buffer such as shell sand, and/or addition of calcium or potassium hydroxide. The latter should be added to the sump (where one is available) to reduce risk to fish or plants of strong alkali; otherwise great care will be required. While shell sand or coral is effective as buffer, calcium hydroxide and potassium carbonate may give better plant growth for some species – especially when combined. While leafy vegetables prefer a high nitrogen: potassium (N:K) ratio, fruits for example prefer higher levels of potassium.

In media based systems or where physical water filtration is used, anaerobic conditions may develop, and this has the opposite effect – leading to a rise in pH, which may not suit plants, and which increases the proportion of toxic (unionised) ammonia. Furthermore, if this happens, limiting nutrients such as potassium and calcium cannot be supplemented in the buffer because they would further raise pH[39]. However, Rakocy has suggested manipulation of the level of de-nitrification in the system as a means of adjusting pH and the N:K ratio.

In practice - however it is achieved - the target pH is likely to be compromise between the various requirements of fish, plants and bacteria. Optimum pH for health and nutrient uptake in plants is usually in the range of 5.5 to 6. For example, earlier harvests of cucumber have been recorded at pH 6[40]. Nitrifying bacteria on the other hand perform best (in terms of ammonia reduction) at pH levels of 7 to 8.5[41] . Fish are usually intermediate in their requirements, generally preferring pH 6 to 7.

6.2.3 Other water quality parameters

Other relevant water parameters include electrical **conductivity**, which should be maintained in the range between 2-4 dS m-1 or less to avoid plant/leaf phytotoxicity[42]; **alkalinity** above 100 mg/l for optimal nitrification buffering[43]; **BOD**[44] below 20 mg/l to avoid anaerobiosis; and dissolved oxygen (**DO**) above 5 or 6mg/l for optimal fish, plant and bacterial growth and health[45].

6.2.4 Optimising nutrient concentrations and the importance of feed

Optimal nutrient concentrations and formulations for plants are well established[46]. Nutrient requirements (concentrations and ratios) may however vary according to growth stage[47], which can be a challenging factor in aquaponic systems. For example, although high nitrate concentration favours vegetative growth in leaf vegetables, lower concentrations are appropriate during ripening of fruiting vegetables[48]. Low concentrations of potassium may limit

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[39] Lennard "Fact Sheets" Plant:fish ratios www.aquaponic.com.au

[40] Rakocy J.E, Masser M.P. and Losordo T.M. (2006) Recirculating Aquaculture Tank Production Systems: Aquaponics-Integrating Fish and Plant Culture [Internet] SRAC Publication No. 454 (revision November 2006) Department of Agriculture, USA Available from: https://srac.tamu.edu/index.cfm/event/getFactSheet/whichfactsheet/105/ (accessed on 20 July 2013); Losordo T.M, Masser M.P. and Rakocy J.E, 1998. Recirculating Aquaculture Tank Production Systems An Overview of Critical Considerations. SRAC Publication No. 451, September 1998 - Revised, Tyson, R.V., Simonne, E.H., White, J.M. and Lamb, E.M. 2004. Reconciling water quality parameters impacting nitrification in aquaponics: the pH levels. Proc.Fla.State Hort Soc. 117:79-83

[41] Tyson, R.V., Simonne, E.H. and Treadwell, D.D. 2008. Reconciling pH for Ammonia Biofiltration and Cucumber Yield in a Recirculating Aquaponic System with Perlite Biofilters. Hortscience 43(3):719–724.

[42] Resh, 2004 op cit; Rakocy J.E, Losordo T.M. and Masser M.P. (1992) Recirculating Aquaculture Tank Production Systems. Integrating Fish and Plant Culture [Internet] SRAC Publication No. 454 Department of Agriculture, USA Available from: http://ag.arizona.edu/azaqua/extension/Classroom/SRAC/454fs.pdf (accessed on 20 July 2013), Rakocy et al 2006, op cit

[43] Rakocy, J. E., Bailey, D. S., Shultz, K. A. and Cole, W. M. 1997. Evaluation of a commercial-scale aquaponic unit for the production of tilapia and lettuce. Pages 357–372 in K. Fitzsimmons, editor. Tilapia aquaculture:Proceedings of the Fourth International Symposium on Tilapia in Aquaculture at Orlando, Florida. Northeast Regional Agricultural Engineering Service, Ithaca,New York, USA.

[44] Biological Oxygen Demand – a measure of the amount of decaying organic matter and its capacity to remove oxygen from the water

[46] Resh (2004) op cit; Leoni (2003) op cit. and Sonneveld C. and Straver N. 1989 Nutrient Solutions for Vegetables and Flowers Grown in Water or Substrates. Voedingsoplossingen Glasstuinbouw Bull. N. 8. Naaldwijk, The Netherlands

[47] Leoni, 2003 op cit

[48] Van Anrooy R., 2002 Marketing Opportunities for Aquaculture Products in the Lesser Antilles. In: Lovatelli A., Walters R. and van Anrooy R (editors) Report of the Subregional Workshop to Promote Sustainable Aquaculture Development in the Small Island Developing States of the Lesser Antilles FAO Fisheries Report No. 704 SLAC/FIRI/FIPP/R704. FAO, Rome, Italy

fruit setting, ripening and sweetness in fruiting vegetables. N:K ratios of around of 1:1 are desirable for optimal production of tomato and cucumber[49].

A significant weakness of aquaponic systems is that if you balance the system for nitrogen (i.e. nitrogen produced by the fish is mainly taken up by the growing plants), then several other important nutrients – including iron, calcium, potassium, phosphorus, and magnesium - are likely to be limiting[50], though this will depend to some extent on the fish feed and fish species used.

> *It is a constant battle because nothing is constant - fish grow, plants grow, plants get harvested, the biodiversity and the root surface area that house the nitrifying bacteria in the system is constantly changing.*
>
> Larry Yonashiro, Aquaponics No Ka 'Oi, Hawaii

As a result, water chemistry in a stable aquaponic system is significantly different from that in a hydroponic system using stock nutrient solutions in terms of both the concentration of nutrients and the ratio between nutrients (see Annex 3) and this may reduce plant growth[51]. However this is not always the case, which may be explained as resulting from the complex microbial mix which may facilitate root functioning and nutrient absorption. However comparisons of performance of hydroponic and aquaponic systems under commercial conditions remain very limited. Seeking to stabilize aquaponic systems at higher nutrient concentrations is not desirable. Most fish can tolerate nitrate (NO$^{3)}$ levels at 200 mg/l[52] but concentrations above 300 mg/l are toxic.

The normal solution is therefore to supplement the nutrients in aquaponic systems. Chelated iron is added routinely. Calcium and potassium may be added as required in the form of CaOH and KCO_3 which may also be used to adjust pH as discussed above.

Feed rate and feed quality is a crucial factor that will affect the mix and levels of different nutrients in the system. Different diets are appropriate for different growth stages of fish. Diets for pre-adult fish are richer in crude protein (40-50 %), while those suited to mature fish usually have crude protein levels between 30 and 40%. The higher the feeding rate and the protein content, the more nitrogen will be available for plants. The rate of nitrogen excretion by the fish will affect the biomass and area required for plant production; and the ratio of nitrogen to other nutrients will determine the suitability of the nutrient solution for different types of plant.

Trials by scientists from the University of Hawaii[53] have shown that the quality of the feed has a major impact on growth of fish, growth of plants, and quality/chemical composition of plants. It is also likely to have an impact on system functioning – poor quality feeds are associated with more faecal and other wastes, and in the absence of highly efficient settling devices, these solids will tend to build up in the system.

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[49] Savidov, 2005 op cit

[50] Rakocy J.E. and Hargreaves J.A. 1993 Integration of Vegetable Hydroponics with Fish Culture: a Review. In: Techniques for Modern Aquaculture. Proceedings of an Aquacultural Engineering Conference 21-23 June 1993. p 112-136. ASAE. Spokane, Washington, USA; The Freshwater Institute 1998. Suggested Management Guidelines for An Integrated Recycle Aquaculture – Hydroponic System. Version 1.0. [Internet] The Conservation Fund's Freshwater Institute, Shepherdstown, West Virginia, USA Available from: < http://www2.pjstar.com/images/uploads/grobedom.pdf> (accessed on 20/8/2012)

[51] Graber, A. and Junge, R. 2009. Aquaponic Systems: Nutrient recycling from fish wastewater by vegetable production. Desalination 246:147–156

[52] Losordo et al. 1998 op cit

[53] Fox 2013 op cit

6.3 Temperature

In those systems where the intention is to produce both fish and vegetables, there may need to be some compromise over temperature, depending on the species involved. Optimum temperatures for Tilapia growth is 25-30°C; that for most lettuce species 17-25 °C. Carp temperature optimum is 20-26 °C and may be more suitable in many situations, but carp is usually less desirable in the market place.

High temperatures and/or nutrient deficiencies may be responsible for the vegetable bolting problems encountered by some practitioners. This may be a particular problem in many Pacific islands. However good species selection and nutrient management should overcome this problem, and certainly this does not seem to be a major problem with hydroponic growers.

6.4 Production scheduling

The secret of cost minimisation and price maximisation when running an aquaponic system will be to:

a. Ensure that production of both fish and plants is consistent and predictable, and maximises potential production from the system through a rigorous stocking and harvesting regime;
b. Develop direct sales markets in line with the anticipated pattern of production of both fish and vegetables.

> *I am not concerned about selling fish as much as the vegetables, but I do sell the fish occasionally. I learned early on that trying to do both leads to many problems with trying to maintain water quality and nutrient balance in the system.*
>
> Larry Yonashiro, Aquaponics No Ka 'Oi, Hawaii

Given the perishable nature of vegetables and the cost of keeping fish in a recirculated system, failure in relation to either a) or b) will result in high costs, high wastage, and likely financial loss or failure. Poor production scheduling, unused capacity, and lack of balance between supply and client needs has probably been a major factor affecting financial performance of aquaponic systems throughout the world – and especially those run by community groups or initiatives.

In efficient aquaponic systems both fish and vegetables are stocked and cropped on a regular basis to meet both market needs (i.e. regular predictable supply) and to maintain balance between plants and fish. For the fish this implies the need for several tanks, so that if the production cycle is 1 year, one of (say) 4 tanks could be harvested and restocked every 3 months. The more regular or continuous the market demand, the more tanks will be needed. Equally, the shorter the harvest cycle and the more tanks used, the less disruption of the balance between fish and vegetables. Selective harvesting can be used as an alternative, but will result in more stress/disturbance to fish. Plants will normally have a production cycle of 3-6 weeks and again regular harvesting and restocking with prepared or purchased seedlings will be essential to meet the needs of the market, system balance and cost minimisation.

Most extrapolations of financial return from aquaponic systems make the implicit assumption that production will be maximised (100% use of grow-bed space at all times) through efficient rotating production scheduling, and that all produce will be sold at normal market price. Even for the best of systems operated by dedicated, technically skilled and market savvy people, this will rarely be the case, and more realism is needed in financial assessments.

Because of the complexity and constraints introduced by the need to balance the production and marketing of both plants and fish, some producers have effectively "opted out" of growing the fish as a commercial crop, and simply manage the fish as an organic nutrient source.

6.5 Managing disease and pests

6.5.1 The problem

It has been suggested by some that pest control is the greatest challenge for the viability of aquaponic systems[54]. This is because:

- Aquaponic systems are intensive – there is a high density of fish and plants in one location, often of the same or similar species. Spread of disease/pests can be rapid.
- The environment in aquaponic systems – with more limited air circulation around crowded plants – may be conducive to plant pests and diseases
- The bio-security of the fish system, which in stand-alone aquaculture recirculating systems would be rigorously preserved, is compromised by circulation of the water in a relatively open plant system
- The management response to disease or pests is constrained by:
    - the combination of fish, plants and bacteria, since fish may be sensitive to plant treatments and vice-versa; and bacteria may be sensitive to both fish and plant treatments;
    - the desire to maintain chemical free or organic status;
    - the inability to sterilize the system, or remove a significant proportion of the stock, without disruption to microbiology and water chemistry
- The consequences of serious disease are compounded, since losses or removal of either plants or fish will upset the balance between fish and plants and water chemistry

In the extreme, a system may have to be cleaned out of either fish or plants and "restarted". It will then take 6 weeks or so to re-establish a balance between fish and plants, and significantly longer to return to a normal stocking and harvesting regime.

6.5.2 Management options

There are nonetheless a variety of ways in which pests and diseases can be prevented or managed, and there is a great deal of advice on the internet and in various guidance manuals about this[55].

Plant deterrents

Multiple planting with different plant species will certainly help. Many insects will avoid marigolds, buck wheat, and Sunn Hemp. Interplanting with garlic, onions and herbs may also be effective.

Insectary

A variety of insects are predators on some plant pests, including ladybird, braconid wasp, trichogramma wasp, key-hole wasp, aphid collecting wasp, lacewing, hoverfly, tachninid fly, assassin bug, pirate bug, and spider mites. Wasp nesting blocks can be used to attract some of these species.

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[54] Clyde Tamaru pers. com.

[55] See for example Friendly Aquaponics, Inc. Aquaponics pest management. 2012 Supplement to all do it yourself manuals

Plant resistance

There are significant differences between different varieties of plants with regard to susceptibility to disease in different locations, and local testing will be essential to find the most suitable varieties.

Netting, reflectors and other scaring devices

A variety of physical barriers (such as shade netting) and visual deterrents (such as CD strings) may be used to reduce ingress of insects. In Europe and N America, completely sealed buildings or greenhouses may be used, but this is unlikely to be feasible in tropical and subtropical zones where reduced circulation is likely to lead to excessive temperatures. Nonetheless, strategically used shade or in some cases mosquito netting may serve as effective barriers.

Organic pesticides and microorganisms

These are increasingly used in organic vegetable production and include for example *Bacillus thuringiensis* (Dipel, XenTari) which produces chemicals that are toxic to insects. It does not normally occur in water and is not likely to multiply in water, and is practically non-toxic to fish and birds[56]. *Beauveria bassiana* is a fungus that grows in soils throughout the world and parasitizes some arthropod species. It is used to control pests such as termites, thrips, whiteflies, aphids and different beetles[57].

It is too easy to accidentally kill all your fish "Just because a product is "approved for organic use" does not mean it is safe to use in an aquaponics system. There is no magic cure here. Chemical insecticides, oil, and soap, whether conventional or organically approved, should never be used in an aquaponics system.

From the booklet "Aquaculture Pest Management" written by Tim Mann of Friendly Aquaponics Inc, Hawaii.

Homemade treatments

Organic farmers often prepare homemade pesticides, for example using soap or detergent as a base. However this will damage an aquaponic system and may be toxic to fish. Some alcohol based preparations containing garlic and chili may however be effective[58].

6.6 Weeds

A significant advantage of hydroponic and aquaponic systems over more conventional forms of horticulture – and especially organic horticulture – is the lack of weeds, and the reduced labour in relation to this activity.

6.7 Feed and other inputs

Feeding rate may be subject to careful calculation to optimize a system and ensure maximum growth rate of fish and vegetables for minimum food input. In less optimised system the basic rule is to feed regularly (preferably several times a day), and to feed to just less than satiation – i.e. until feed remains in the water for a little while before being eaten.

[56] http://npic.orst.edu/factsheets/BTgen.pdf
[57] http://en.wikipedia.org/wiki/Beauveria_bassiana
[58] Mari Nomura pers. com

As noted elsewhere the quality of feed is critical to the efficiency of the whole system Poor quality feed will result in poor growth of fish (which may or may not be a problem, depending on whether fish is to be a significant product), poor growth of plants, and possibly worse taste and lower nutritional value of plant products. Tests undertaken in Hawaii[59] suggest that the system performed significantly better (Tilapia growth, plant growth, especially Kai Choi) when a quality trout pellet with 45% protein was used compared with a 35% protein catfish feed.

It will also normally be the case that the use of a poor quality feed will result in worse food conversion efficiency and greater production of solids which will have to be removed from the system.

As noted elsewhere a variety of nutrient supplements may also be required including in particular iron. Operators will need to develop skills to recognize and understand nutrient requirements and deficiencies.

6.8 Food safety issues

Foodborne illness is a major cost in all economies. Growing plants in faecal waste from fish, and growing fish in their own recirculated (if partially treated) waste water also raises concerns. Furthermore, a complex microbial fauna and flora is an essential characteristic of the aquaponic system. For these reasons, and given the limited scientific evidence, the USDA is currently unwilling to support food safety for aquaponics[60]. Most third party certifiers of food safety would automatically fail aquaponics because of the use of un-composted animal manure. However, recent work by scientists at Centre of Tropical Agriculture and Human Resources in Hawaii suggests that these systems are in fact safe with no trace of pathogenic *E coli* or *Salmonella* in recent trials.

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[59] Bradley Fox. Presentation to technical Consultation on Aquaponics, Raratonga, Cook Islands, 23-27th September 2013

[60] Fox 2013

7 AN OVERVIEW OF CURRENT GLOBAL ACTIVITY

This section is based on a thorough review of internet sources, both commercial and academic; an online survey which yielded 33 detailed responses; and face-to-face, telephone and email exchanges with researchers and practitioners (including both survey respondents and others). Much of the information collected related to production parameters, and these are dealt with in the next section. Here we consider more general characteristics, operational issues, and present some illustrative case studies and quotes from respondents that provide an insight into running an aquaponics system. An overview of the systems covered in the survey is provided in Annex 4.

7.1 Overall scale and concentration of activity

Our web and literature review revealed more than 100 current or recent significant aquaponics initiatives across the globe for which at least some information was readily available online. Fifty-six of these were in Europe, 35 in the USA, 16 in the Asia Pacific region and several in South America. It is likely that at least as many again are in existence but not "visible", although these are likely to be relatively small scale and mostly "back-yard" type systems.

Of those identified, the majority were greenhouse or indoor based systems in urban areas of temperate regions of Europe and North America. However, several of the larger near-commercial systems were outdoor systems located in Hawaii.

7.2 Types of initiative

The main categories of enterprise or initiative are summarized in Table 2. While many have commercial intent, they are almost all ideologically or research driven, with the primary objective of demonstrating or promoting sustainable, ecological, local or urban food production.

> *It is the only way to feed the world in the future and to save our environment*
>
> Aquaponics Trainer, supplier (??)

In most cases aquaponic fish and vegetable production is part of a broader based business, community enterprise, research organisation, consultancy/training provider, or equipment supplier. Although several survey respondents claimed to be "commercial", close inspection of responses showed that out of 34 respondents, only one was arguably fully commercial and did not appear to rely on income from non-food production parts of the business. Indeed, several on-line respondents suggested that aquaponics could not be viable as a stand-alone business. The reasons for the relatively limited commercial activity – at least on an SME scale – are probably related to the costs, risks, marketing and management challenges presented by integration.

The closest to fully commercial that we found were those based in Hawaii, which is perhaps not surprising. There is a combination of strong research and advisory support, high priced vegetables related to poor soils or limited water in some islands, and significant interest in sustainable and local food production.

We have found no evidence of any purely commercial aquaponic production of fish and vegetables where the technology was chosen as the most cost-effective method of production. Entry was usually driven by a belief that this is the future of food production; by a desire to trial a new technology; and in many cases because the concept is regarded as particularly suited as a focus for community initiative and attractive to donors.

All operations appeared to rely on a niche market and price premium, associated in most cases with a local farm shop, visitor attraction or café outlet. Others were able to sell into more mainstream but high value markets (e.g. in Hawaii) and generate a small “sustainability” or organic premium.

Table 2: Types of aquaponic enterprise

Type	Key characteristics	Funding/profitability/motivation
Kitchen window	Very small scale household systems suitable for growing a few herbs and salad	Convenience/quality of life/interest rather than profitable
Backyard/smallholder	Small scale enthusiasts system similar to owning a greenhouse for home vegetable production	Primarily a hobby activity but yielding significant production for home consumption and sharing with neighbours.
Research/demonstration	Small-medium and medium-large systems designed for research and demonstration purposes	Primarily research funding; may sell some produce to contribute towards running costs; excellent education/training tool
Community initiative	Varied in character but typically medium scale enterprise built using public funds and operated by local community NGOs. Often combined with waste recycling initiatives, work placements, and/or organic and local food initiatives	Usually public investment from local, national, regional and international social and economic development funds
Sustainable food outlet	More commercial and entrepreneurial	Funding for the aquaponic system is either cross subsidy from the food outlet, or enhanced margins related to sustainability image
Sustainable research, training, supplies and consultancy services	Selling “sustainability” – ideas, products, services, training, research	Primarily from sales of equipment and services rather than from fish/vegetables
Organic hydroponics	Primarily a hydroponics vegetable production system using fish a source of organic fertilizer and sustainability image booster	Primarily from sales of vegetables in premium gourmet, organic and local markets
Organic recirculating aquaculture	Primarily intensive fish production in recirculation system with fertilization of vegetables as secondary waste treatment	Intensive aquaculture has a mixed reputation with regard to input use and waste generation, and this is an attempt to minimise waste from intensive production systems while at the same time benefitting from organic or sustainability credentials/image
Smallholder integrated fish-agriculture systems	Fish grown in ponds; vegetables grown in ponds; pond sludge used to fertilize plants	Primarily subsistence systems, still common in S and SE Asia, but generally in decline and being replaced by more specialist intensive systems

7.3 Scale of enterprise

The survey revealed significant levels of investment with several relatively large scale enterprises (Figure 14) with 7 of the 32 systems more than 1,000m^2 in total size.

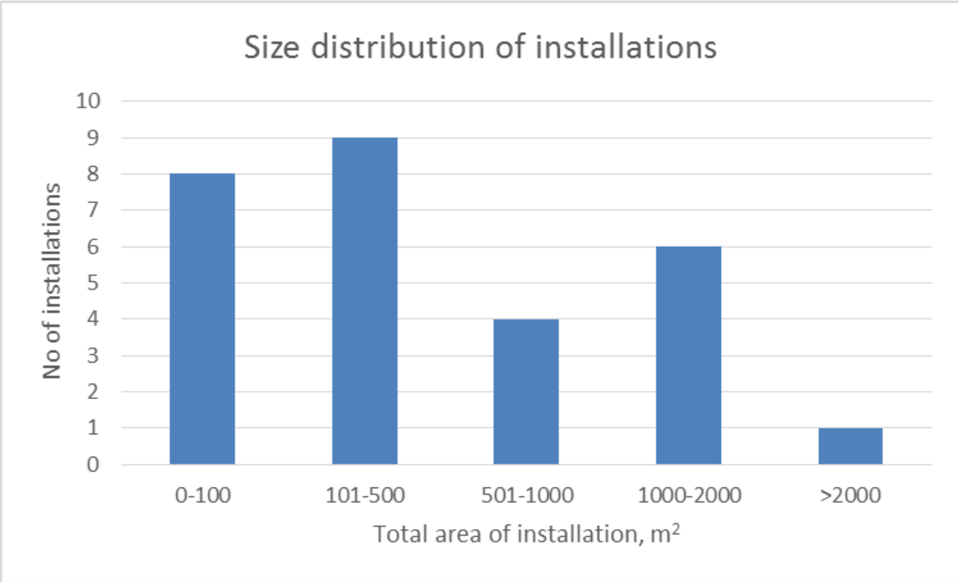

Figure 14: Size distribution of surveyed systems

Investment was highly varied, but with several major investments. Five of the respondents had invested more than US$50,000 and 3 had invested more than $100,000. At the other extreme were "kitchen window" systems of less than 1 square metre, and costing a few hundred dollars.

7.4 Operational issues reported by aquaponics practitioners

In the online survey we asked people to list or describe the most frequent or serious management or operational issues they had to contend with. These included:

- Bolting and leaf burn
- Nutrient deficiency, calcium deficiency, iron deficiency
- Light deficiency
- pH problems
- Algal growth
- Pests and disease, including aphids, whitefly, ants, phytoplasma (bacterial parasites of plant phloem), caterpillars (leafy vegetables), powdery mildew, thrips, red mites (beans),
- Lack of fruiting in vegetable fruit crops
- Clogging sand media

7.5 Case 1: Garden Centre with aquaponics - Tropics

Key quotes

> *"Aquaponics is an extremely tricky process. It's all about water chemistry and dissolved oxygen levels.*
>
> *Know your costs and set your price, do not be a price taker. Develop your market before you grow because there is no time to market while you are harvesting."*

This is an upmarket plant nursery and garden centre intertwined with an aquaponics venture. It is in a semi-rural area close to a national park and within easy driving distance of a city whose population are largely well-educated and mobile. The climate is tropical, with a very small seasonal variation in temperature range. The site is 18 acres, and is primarily a plant nursery selling mixed species ornamentals, palms and turf together with elegant garden décor. There are many small backyard aquaponics ventures in this area but this is one of the first to go commercial. One acre is given over to aquaponic production of tilapia with lettuce, tomatoes, cucumber, green onions and other vegetables. Fish effluent is also used to replace commercial fertilisers for some of the trees, turf and greenhouse plants. This is an organised and professional family business with a high media profile, run by a small group of skilled and articulate people. The business began in 1976 and has been operating on the present site since 2008.

Technicalities

They suggest that aquaponics is a tricky business and that water chemistry and dissolved oxygen level are critical. They add only chelated iron to the water, with no additional fertilisers or pH adjustment. Composting worms are used in the biofilter. Vegetables and fish are kept as covered as is possible to reduce algal growth and evaporation. No artificial heating is needed. Water use is thought to be fairly minimal. Homegrown duckweed is fed to the tilapia and makes up about 20% of their feed.

The market

This business produced about 300lbs of tilapia a week. This finds a ready market at a good price in the nearby city. Vegetables are sold on site and through local shops and farmers markets. There is a charge for a tour of the aquaponics area. Conventional advertising is minimal, although the business has a presence on Facebook and Twitter and a good website with interesting videos.

Prospects

Does the aquaponics venture actually pay? Six months into the scheme the owner said that there was no money in it. Yet he and his family and staff were clearly enthusiastic, good with the fish, hopeful for the future.

7.6 Case 2: Smallholding producing a variety of sustainable products and offering training in northern Europe

Key quotes

> *"Aquaponics is great as part of a total food production set-up but it would be difficult to exist commercially as a stand-alone. Lots have tried - most have fried."*
>
> *"If you factor in the cost of start-up money; buildings, polytunnels, greenhouses, tanks, fish, growbeds, then getting the investment back will take ages, let alone earning a living."*
>
> *"There are a lot of people out there spouting nonsense about fortunes to be made from aquaponics and it is nonsense."*

This is a small farm, a smallholding, in a rural area in N Europe. There is a small town close by, and villages, but no cities within easy distance. The business is run and worked by an enterprising, knowledgeable and stoic couple, who have come through recent troubles including the loss of a polytunnel to bad weather. They lost a few months growth and sales but have tidied up and repaired the considerable damage and are back up and running and offering a raft of training courses for summer 2014. They run both aquaponic and hydroponic systems and also grow crops in the field, keep pigs, make ointments (particularly for chapped skin) and run the training courses and tours. The fish are rainbow trout, sold fresh or frozen and the crops mainly herbs, brassicas and watercress. It is too cold for tilapia or catfish. They started work on the aquaponics system in 2008 and have been operating with their present system (home-built) since 2010. The climate is temperate maritime, wet, windy and somewhat hostile. There is no harvesting in January and February; it is simply too cold.

Technicalities

The rainbow trout are fed high protein commercial trout feed and no extra bought-in fertiliser is added to the aquaponics system. They can harvest fish all the year round, 300-400 a year. In the winter the cold and the low light virtually halt plant growth. It takes about thirty hours a week each to run the entire business.

The market

This works for a local market, it meets local market needs and they have tailored the vegetable growing to this. The trout are very popular, and maybe they act as a draw to assist in selling the other produce. The area is not overwhelmed with retail attractions, it is likely that there is a good neighbourhood network of friendly people and perhaps some passing trade en-route to a nearby ferry terminal.

Prospects

The business breaks even because aquaponics forms just one arm of the company and because of the multi-talented, stoic owners and their healthy fish. But would they make more money without it? Very hard to say.

7.7 Case study 3: Large greenhouse based operation in North America

Key quotes

“We’ve been in this for five years and have yet to make a profit.”

“We are still spending more than we bring in every month”

This is a large commercially orientated operation, working entirely under cover in greenhouses and fish rooms. They have about three hundred tilapia, kept entirely to fertilise the commercial crop of lettuce and herbs, produced all the year round.

Technicalities

No fertiliser is added at all, the fish effluent is all that is used. All the plants are grown from seed, and the fish are brought in as tiny fingerlings four times a year. Harvesting and delivering the lettuce takes six to nine hour a day, with cleaning and planting seedlings to be done as well. Someone else does the fish; this may be only a two-person operation. They use “too much” power.

The market

They harvest about 700 heads of lettuce a week, having just undergone a major expansion. They are now trying to get more customers. They do not sell the fish. It may be that they do not have the food certification documents required to legally sell the fish, or feel that the expense of meeting these standards is not justifiable.

Prospects

This operation has expanded before being sure of their market and also are not selling their tilapia. They have on their own admission not made a profit in five years. Yet they still work hard in the business and see the future of aquaponics as being bigger and better. They see this as “the future of growing food for the world in a pure, clean, natural system without chemicals” and believe that “we have way too many chemicals in the food we eat”. Many of our non-commercial, research or community-based survey respondents expressed similar ideas, but had not tested the practicalities of the system in a commercial environment. This is a brave attempt at a full-scale experiment, perhaps without benefit of much outside marketing assistance or business planning.

7.8 Case study 4: Aquaponics production, demonstration and training in North Pacific

Key quotes

"We are committed to undoing the industrialisation of our food supply: We are living at the end of a fragile supply chain."

"It is impossible for third-world people to buy or run high-tech, high cost aquaponics systems that depend on electricity 24/7."

This is a small business with big ideas. They sell plans for appropriate technology aquaculture systems, they share knowledge through training courses and free open-source advice and they run various thriving systems themselves, doing much practical research and development. They disapprove of off-the-shelf systems that cannot deliver what they promise, particularly in a third world situation.

It is a small family business run by a couple who have backgrounds in biological science and engineering. It is in a rural area in a tropical climate, remote but in a developed market economy. They started the business in 2007, and income comes from selling produce at the farm gate shop, running a full programme of training courses and selling plans for various DIY aquaponics systems. The courses equip people with the DIY competence needed to build and run their own systems. They were the first aquaponics venture to get USDA organic certification and have written a booklet on pest control for aquaponics systems. They keep the minimum number of fish needed to fertilise the vegetables. They grow a variety of vegetables and herbs, selling all the year round. The planting system, home-designed, is very high density; the site is only one-third of an acre.

Technicalities

There is no bought-in fertiliser; all is done with fish effluent. The fish are tilapia, catfish and ornamentals and come from their own on-site hatchery and nursery. They also grow freshwater prawns. Various aquaponics systems are used, all home-designed and built.

The market

There is overwhelming dependence on imported food here, and with the feeling of vulnerability that comes from being at the end of a long supply chain comes a great interest in self-sufficiency and in growing fresh produce locally. There is a market for training courses aimed at enabling this, and the owners are not afraid of local competition; one of their business aims is to increase the use of local aquaponic systems. The fish currently sell at a loss due to the market and to the cost of electricity, fish food and labour. They did have a contract with a very large supermarket for vegetable sales but have found it better to sell just at the farm gate.

Prospects

Innovative, capable people, generous with their expertise, with a technically effective business and with good ideas for appropriate technology third world aquaponics systems and for a local fish food facility using agricultural waste and solar energy.

7.9 Lessons learned

The review of global activity conducted through the online survey and informal exchanges with a wide range of researchers and practitioners suggests the following:

- Aquaponics has been driven by sustainable food production ideology, not by market demand or cost effective technology.
- Capital investment is usually substantial, and investment of time and dedication through a long learning process (often system specific) is typically very high.
- Most systems are not economically viable and would not survive without some form of subsidy or cross-subsidy.
- Those who have nonetheless survived, and who may be regarded as commercial or near commercial have done so by highly effective niche marketing and/or diversification into retail/café/visitor attraction/equipment supply/training and consultancy.
- Clearly there has been more success in those locations where the price of vegetables is very high.
- In many systems fish are not regarded as a significant commercial crop in their own right, but rather as a source of organic nutrients.
- Energy costs are flagged up as a significant issue in many systems.
- Operational problems are common and include nutrient deficiency issues, bolting, pests and disease, lack of fruiting in fruit vegetable crops.
- Actual performance (as revealed by analysis of information on production parameters) is typically far below “design parameters” as presented in scientific literature or in specifications for off the shelf or custom designed systems.

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8 ECONOMIC CHARACTERISTICS

8.1 Production parameters

Production parameters, along with costs of inputs and value of outputs, will determine economic viability and efficiency compared with alternative options for food production. These parameters have been extensively researched in demonstration systems. The following summarizes this research[61] with respect to key parameters, and compares with practical data derived from survey and discussions with practitioners.

A summary of parameters which may be important for design and/or operation are given in table 5. These parameters, together with input costs, ultimately determine cost of production and have been used to develop a set of simple financial models that allow for the estimation of likely cost of production in different situations.

8.1.1 Fish : plant ratios and nutrient balance

The operating ratio of fish:plants in aquaponic systems required to maintain desirable water quality for both fish and plants will depend on many factors, including:

- the scale and sophistication of settling and biofiltration;
- the use or not of anaerobic bio-filtration (which removes nitrogen from the system);
- the volume and surface area of the whole system;
- the quality (nutrient composition) of feed;
- the feeding rate;
- the species of fish and species of plant;
- the temperature and oxygen saturation of the water;
- the accumulation of organic matter and the extent of anaerobic zones; and
- the system potential for root development.

Broadly speaking the operating ratio of plants to fish will be higher in systems without dedicated biofiltration, or to put it another way, if a high ratio of fish:plants is required, highly effective settling and efficient biofiltration will be needed.

Scientific literature

Given these variables, it is not surprising that the ratio of plant production: fish production found in the scientific literature is highly variable - varying by up to a factor of 5. The ratio is often presented in different ways (for example as the ratio of fish standing weight to plant production rate; fish feed input to plant biomass etc.) and this makes comparison very difficult. The most consistent ratio is likely to be that based on feed (=nutrient) input, but even in this case the nutrient content and digestibility of fish feeds varies substantially, and the proportion of input nutrients that end up in the fish and plants will vary depending on solid waste management, efficiency of any biofiltration, the extent of anaerobic activity in the system, the growbeds and biofilters, and species of fish and plants.

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[61] including Watten and Buschs, 1984; Mc Murty et al, 1990, 1997; Seawright et al. 1998; Alder 2003; Resh, 2004; Lennard 2004; Lennard and Leonard, 2006; Savidov, 2005; Verdegem et al., 2006; Rakocy et al., 1992, 1997, 2004, 2007; Tyson et al. 2008; Al-Hafedh et al., 2008; Graber and Junge, 2009; Endut et al 2010; Pantanella et al., 2010, 2011, 2012b; and Dediu et al, 2012).

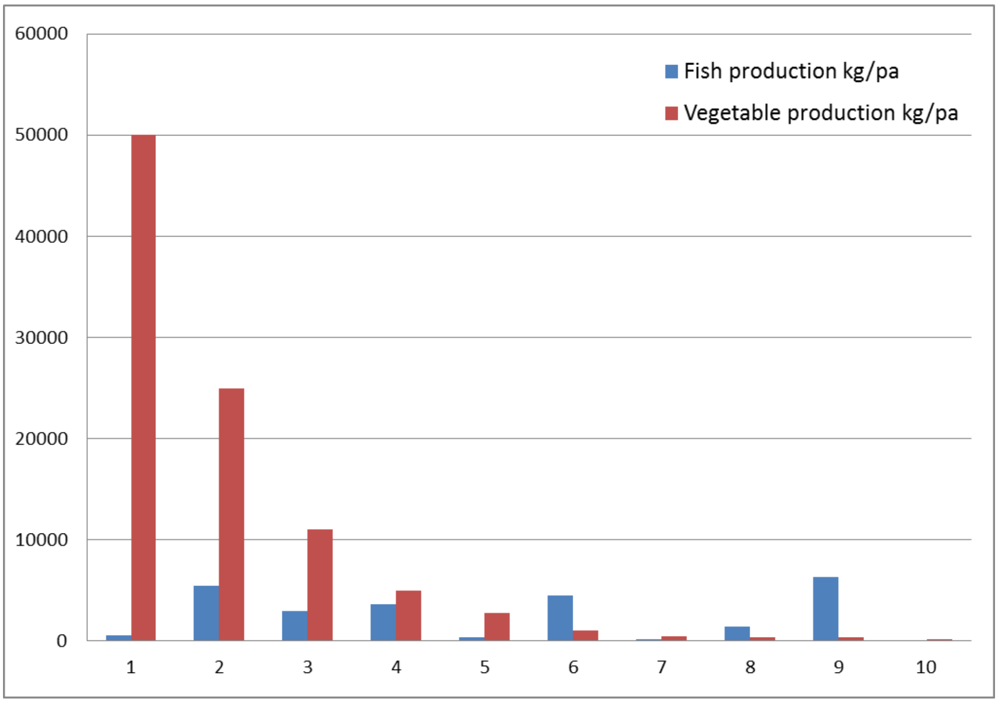
Broadly speaking, in order to maintain a reasonably balanced system in terms of inputs and outputs, the ratio of both vegetable to fish production, and vegetable to fish area, is likely to be in the range of 5-25:1.

A high rate of feeding, coupled with alternative methods of nitrogen removal (such as anaerobic filtration) will at least partially compensate for the relative scarcity of other nutrients in a typical aquaponic system, and reduce the requirement for nutrient supplementation. However, this rather defeats the rationale behind integration (i.e. to use the waste nutrients for plant growth).

Practice

Data collected from the on-line survey was highly variable. The ratio of annual plant: fish production in 10 systems for which comparable data was available ranged from 0.2 to 93 with an average of 12. However three of the producers were quite explicit – fish production was not an objective in itself; it was simply a means to generate organic nutrients. Others clearly sought to produce fish with vegetables as a side crop (Figure 15)

Figure 15: Ratio of fish: plant production in 10 survey responses



When design parameters, such as those used by UK aquaponics are analysed, the ratios are more consistent and vary between 12 and 25 to 1.

The baseline ratio used in the financial models is taken as 15:1.

8.1.2 Water requirements

Water consumption in aquaponics is related to both fish and plant production. Water is discharged as wastewater, lost through the plants' evapotranspiration, and by evaporation from tanks and other components, depending primarily on the nature of aeration. Research over many years has estimated the required replacement rate of water at between 0.5 to 4.6%

of the total system volume per day[62]. Losses will be lower in greenhouse systems and/or where more advanced aeration or oxygenation systems are used, compared with systems in open field conditions[63].

Actual water consumption per unit production for aquaponic and recirculating aquaculture systems will depend on the efficiency of production, and has been estimated at between 0.25 and 1.4m^3/kg of fish production[64]. Assuming a 15:1 plant: fish ratio, this would correspond to between 17 and 93l/kg of plant production. This matches broadly the assessments based on published evaporation/water makeup rates.

In general aquaponics (and especially floating raft system) is likely to consume more water and more power than hydroponics, because of the need for intensive aeration which increases evaporation. It was reported for example that floating raft type aquaponics consumes 70-130% more water than hydroponics[65]. However, many hydroponic operators periodically dump nutrient solution in order to prevent build-up of pathogens and undesirable chemicals, and this reduces water use efficiency. Aquaponics operators cannot do this (which may be regarded as either a weakness or a strength). The overall balance is therefore unclear, and likely to be highly variable dependent on local conditions, operating protocols, and the need to conserve water.

For the purposes of comparison and benchmarking a mid-range value of 40l/kg of production is assumed.

8.1.3 Plant production rates per unit area

Production rates of vegetables in hydroponic and aquaponic systems are typically around double those achieved in more conventional horticulture, but again figures are difficult to compare because of differences in cropping cycles and growing conditions (e.g. temperature). Given the high investment and operating costs in aquaponic systems, productivity will have a very great impact on cost of production and we have therefore researched this parameter in some depth.

Science

Production rate will depend on the stocking/production cycle, the planting density, and the growth rate. Commercial planting densities for (e.g.) lettuce are usually in the range of 20-

[62] Naegel, L.C.A., 1977. Combined production of fish and plants in recirculating water. Aquaculture 10:17-24;
Watten, B.J. and Busch, R.L. 1984. Tropical Production of Tilapia (Sarotherodon aurea) and Tomatoes (Lycopersicon esculentum) in a Small Scale Recirculating Water System. Aquaculture 41, 271-283;
McMurty, M.R., Sanders, D.C. and Cure, J.D. 1997. Efficiency of Water Use of an Integrated Fish vegetable Co-Culture System Journal of the World Aquaculture Society 28:420-428;
Rakocy, J. E., Bailey, D. S., Shultz, K. A. and Cole, W. M. 1997. Evaluation of a commercial-scale aquaponic unit for the production of tilapia and lettuce. Pages 357–372 in K. Fitzsimmons, editor. Tilapia aquaculture:Proceedings of the Fourth International Symposium on Tilapia in Aquaculture at Orlando, Florida. Northeast Regional Agricultural Engineering Service, Ithaca,New York, USA;
Rakocy J.E., Shultz R.C., Bailey D.S. and Thoman E.S. (2004) Aquaponic Production of Tilapia and Basil: Comparing a Batch and Staggered Cropping System. pp 63-69 In: South Pacific Soilless Culture Conference - SPSCC. Acta Hort. 648. ISHS, Leuven, Belgium;
Savidov, 2005 op cit;
Al-Hafedh, Y.S., Alam, A. and Beltagi, M.S. 2008. Food Production and Water Conservation in a Recirculating Aquaponic System in Saudi Arabia at Different Ratios of Fish Feed to Plants. Journal of the World Aquaculture Society, Vol. 39,510:520
[63] Savidov, 2005 op cit, Al-Hafedh et al., 2008 op cit
[64] Verdegem, M.C.J., Bosma, R.H. and Verreth, J.A.J. 2006. Reducing water use for animal production through aquaculture. Water Resources Development 22:101–113
[65] Pantanella, E, Colla, G, Appelbaum, S. 2012b Sustainable Aquaculture and Farming Systems: Water Use Efficiency in Aquaponics. . Drylands, Deserts and Desertification conference. Ben-Gurion University of the Negev. November 12-15, 2012. Sede Boqer Campus, Israel

40/m^2 although rates as high as 50-60/m^2 are possible (Fox pers. com). It is likely however that growth rates would be constrained by more limited spread and light at such high densities.

According to the literature, rates of production of herbs and leafy vegetables in aquaponic (and hydroponic) systems are likely to be in the range of 2-6kg/m^2 per 3-5 week crop[66]. Based on substantial experience Resh[67] suggests typical production rates of lettuce at 2.3kg/m^2 per crop, which might translate to 23kg/m^2/year for locations where year round production is possible.

Yields of cucumber may be 7kg/m^2/crop. In an efficiently run tropical or sub-tropical system we might therefore anticipate 20-40kg of leafy vegetable production per m^2 per year.McMurty et al.[68] projected annual yields of 30-60 kg/m^2 of tomato, and 60-80kg for cucumber/m^2/yr. Higher rates have been recorded for semi-aquatic species such as water spinach. Production rate in the University of the Virgin Islands systems have been recorded as high as 338g/m^2/day corresponding to over 100kg/m^2/yr, but this probably corresponds to maximum rate of uptake – i.e. as the plants approach maturity. Clearly rates will be very much lower in the early stages of production and an average crop cycle value is therefore a more useful parameter.

Practice

In many of the survey responses it was not possible to distinguish area associated with fish and area associated with plants. The main corresponding parameter from the online survey was therefore annual plant production/m^2 of the whole system. This parameter ranged from 1 to 100 with an average of 25 (15 systems).

An actual example of an estimate of annual average productivity based on a real world planting and harvesting regime is presented in Table 3.

Table 3: Example of potential maximum productivity Hawaii[69]

Crop type	Wgt, kg	cycle
Bok choy summer	0.13	5
Bok choy winter	0.07	5
Lettuce summer	0.07	4
Lettuce winter	0.06	4
Annual production assuming 50:50 lettuce: Bok Choy		
Total area	48	
harvest cycle (average)	4.5	
plants/m^2	51	
plants/m^2/yr	591	
weight of plants	0.09	
production/m^2/yr	50	
% of maximum crop achievable[70]	80%	
Adjusted production rate kg/m2/yr	**40**	

66 Based on planting density around 20-40plants/m2
67 Resh 2004 op cit
68 McMurty, M.R., Sanders, D.C. and Cure, J.D. 1997. Efficiency of Water Use of an Integrated Fish vegetable Co-Culture System Journal of the World Aquaculture Society 28:420-428
69 Based on actual production data Larry Yonashiro pers com
70 This allows for the fact that no production system will operate year round at maximum capacity – an allowance has to be made for losses and inefficiencies (pests, bolting, seed failure etc). In most cases these will be substantially more than 20%

Design parameters for commercial systems typically assume between 20 and 80kg/m^2/yr. For the purpose of the financial models a baseline value of 40 is assumed.

8.1.4 Fish production rates per unit volume

Science

Annual production will depend on stocking and harvest density, growth rate and harvesting regime. Recommended stocking densities for Tilapia are typically in the range of 20-40kg/m$^{3.}$ It should be possible to grow a 500g Tilapia in one 1 year, and if the fish are harvested and restocked on a quarterly basis, it should be possible to achieve an annual production of roughly double the standing stock.

Quoted yields in the literature are usually in the range of 30-70kg/m^3/yr for tropical/sub-tropical systems, though some UVI data suggests double this rate. In practice however, most systems use significantly lower stocking densities with correspondingly lower annual yields.

Practice

Fish production rates derived from survey responses varied hugely from 5 to nearly 400 kg/m^3/yr, but most figures were in the range of 30-70 kg/m^3/yr

A baseline rate of 50 is used in the financial models.

8.1.5 Fish and vegetable production

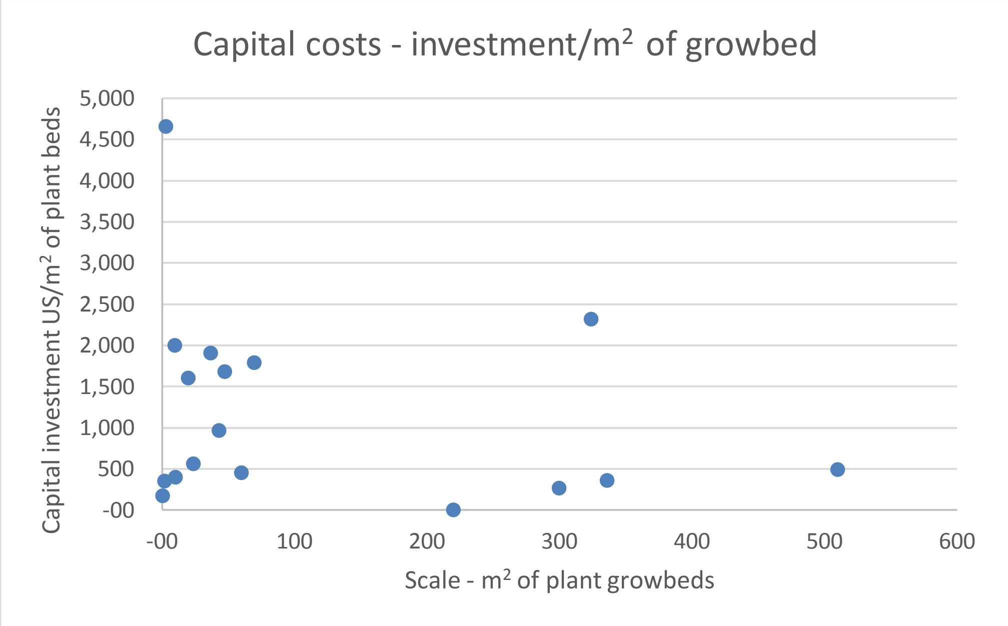
Given the dominance of the growbeds, it is useful to derive a total figure for overall production of fish and vegetables per m^2 of growbed. In the survey and other systems this parameter varied between 3 and 160, but with the majority of values between 30 and 80 kg/m^2/yr. A reasonable ball park figure based on the above parameters would therefore be 100 kg/m^2/yr. Assuming tanks and growing beds take up 50% of total site space, this would be equivalent to 15-40kg/m^2 of site.

8.1.6 Investment requirements

Small off the shelf backyard aquaponics kits are widely available online at 1 to 2 thousand dollars per m^2 of growbed.

From the online survey, average investment costs per m^2 of plant growbed averaged just under US$1,000 but with a very large variation ($162 to 4,665) (Figure 16). In their on-going study researchers developed a “model” commercial system, with growbed area of 1,142m^2, with a cost of roughly $190/m^2 suggesting significant economies of scale are achievable.

Figure 16: capital costs as a function of grow-bed area



This very large variation is related to the fact that some of these systems were part of sophisticated indoor or greenhouse based visitor attractions. Closer examination of more specialist semi-commercial aquaponics systems still reveals wide variation however, with most systems costing between $300 and $1, 700 per m^2 of growbed area. Those at the top of the range were typically commercially commissioned systems, some with greenhouse structures; those at the bottom simpler systems put together by handy owners. The two cost clusters at the lower end of the size range in Figure 16 illustrates the difference between purchasing a commercially available kit, as oppose to putting together a one-off system using locally available units. At the bottom of the range, one of the authors has estimated materials and equipment costs for a 34m^2 system in Asia at a mere $16/m^2 of growbed. Although costs will be significantly higher in Pacific Islands, this illustrates what is possible for a motivated small scale enterprise.

Of particular relevance to systems in the Pacific, a 43m^2 floating raft system in Hawaii came in at $1,681/m^2 growbed area; while the New Zealand Aid Progrmme funded project in Raratonga cost close to $1,000/m^2 of growbed area. These relatively high costs reflect in part the generally high costs of importing equipment to the islands.

For the baseline model we assume $1,000/m^2 growbed for a fully commissioned robust and well-designed system for commercial production, and $200/m^2 growbed for a simple homebuilt backyard system. The on-going work of researchers at the University of Hawaii suggests this might be significantly less for a larger scale commercial system, but this would involve initial investment of over $200,000.

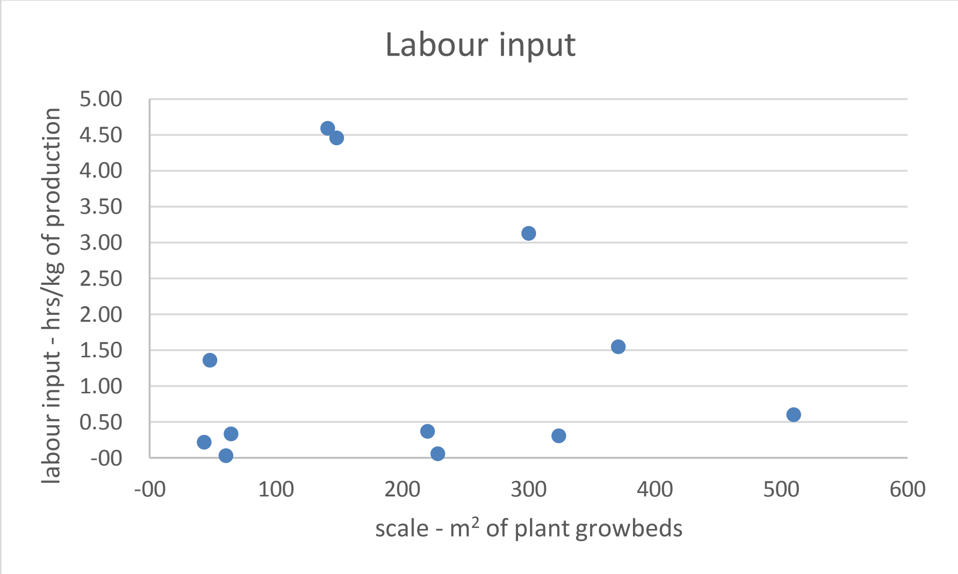
8.1.7 Labour

We have been unable to find estimates of labour input requirements from the scientific literature, and this has been a major weakness of many demonstration projects to date. This is a common weakness in technical research and demonstration.

We were however able to glean some data from our online survey, though this is quite difficult to interpret and comes from widely divergent systems.

Average labour input derived from the online survey ranged from 0.04 to 1.44hrs/kg of production with an average of 0.44 and median 0.3-0.4. Clearly economies of scale are likely to be important, and labour input v scale of production is plotted in figure 17.

Figure 17: Labour input to aquaponic systems



Estimated labour (cost benefit analysis) for the system in Rarotonga was 0.25FTE for a system designed to produce a maximum of just over 4t of lettuce pa, corresponding to labour of 0.12hrs/kg of product.

In practice labour is more likely to relate to the number of plants handled than to the weight of produce. Although production cycle for smaller plants such as herbs may be more rapid, the labour/handling/replanting costs will be significantly higher.

A more detailed example of the breakdown of actual labour costs in a near commercial system in Hawaii is presented in table 4.

Table 4: Labour input SME aquaponic system[71]

Activity	**hrs per plant sold**
Harvest (setup, cleaning, delivery)	0.03
Prepare medium, clean net pots, seed and plant	0.05
Inspect, spray, repair, shop, admin	0.02
Misc	0.03
Total labour - hrs/plant sold	***0.13***

[71] Source data provided by Larry Yonashiro. For their system this equates to roughly 1FTE for a system capable of producing around 1500kg of lettuce and Bok Choy a year

Taking average plant weight (lettuce, bok choy) at 250g, this equates to roughly 0.5hrs/kg of production. The owner however concedes that this could be reduced significantly if they were to work flat out.

For the baseline we assume a 0.4hrs/kg of total production.

8.1.8 Energy

Power is required to drive pumps and aeration devices (blowers and air pumps), and in some of the systems designed for temperate climate, heating in winter and occasionally cooling in summer. Energy costs will also depend on the type of system, the efficiency of the pumps and aeration, the design of the pipework, and the scale of the system. Smaller pipes for example, with many elbows, will create far more friction and increase the effective pumping "head". In general raft systems are likely to consume more power because of the need for intensive aeration of grow-beds in addition to aeration of fish tanks. Some smaller media bed systems dispense with aeration altogether, relying on trickling or spraying of pumped water for aeration. However this is unlikely to reduce power costs per unit production because aeration by pumping necessarily involves a loss of pumping head. Furthermore, significant energy is required for intensive aeration for the fish alone if they are to be healthy and grow well with high food conversion efficiency. As much as 0.5kw is required for 1,000lbs of fish, which corresponds roughly to 10 kWh per year for every kg of fish held in the system.

It should be noted that power draw is generally higher than that suggested by pump or blower rating – typically 30% (Yonashiro pers. comm.) and this has been confirmed by examining power consumption at other currently operating systems.

From the point of view of a useful production parameter, energy consumption might be measured relative to the system volume, the productive volume of fish, the total production of fish and plants (Figure 18) or the productive area of plants (Figure 19). From the point of view of financial modelling, energy use per m^2 of grow-bed area is probably the most useful parameter, because energy costs are relatively fixed irrespective of output, and in most systems (which are vegetable dominated) the area of functional grow-bed is the primary determinant of potential production.

Again figures from the survey are widely divergent from 1 to 25kWh/kg of production and of production or 26 to 556kWh/m^2 of plant production. Given this variation we explored in much more depth some specific examples where data was known to be reliable and where experience and explanations could be provided by operators.

At the demonstration site in Raratonga (40m^2 of plant grow-beds), actual power consumption for blower and two pumps is 5700 kWh/yr, which corresponds to 133kWh/yr/m^2 of grow-beds, or 2.7kWh/kg of production if we assume a relatively optimistic production rate of 50kg/m^2/yr (production is currently well below this). Another near commercial system from Hawaii consumed roughly 61kWh/m^2 grow-bed/yr, equivalent to roughly 1.9kWh/kg of production at full production (which has still not been achieved). Data is readily available and reliable for small scale backyard systems which are usually significantly less efficient, consuming 40-60watts for 1-2m^2 of grow-bed area, corresponding to 170-256kWh/m^2/yr.

An alternative approach is to look at system design specifications – for example as used by "UK Aquaponics". These range between 86 kWh/m^2 of grow-bed per year for relatively simple systems without heating, to 423 kWh/m2 of grow-bed for a highly sophisticated indoor system. One of the authors of this report believes it is possible to achieve as little as 26 kWh/m^2 of grow-bed per year, but this remains to be demonstrated in operational terms.

For the baseline model we assume a range of different rates dependent on scale, but with a baseline for medium scale systems of 80kWh/m^2 of grow-bed.

Figure 18: Energy consumption per unit of production

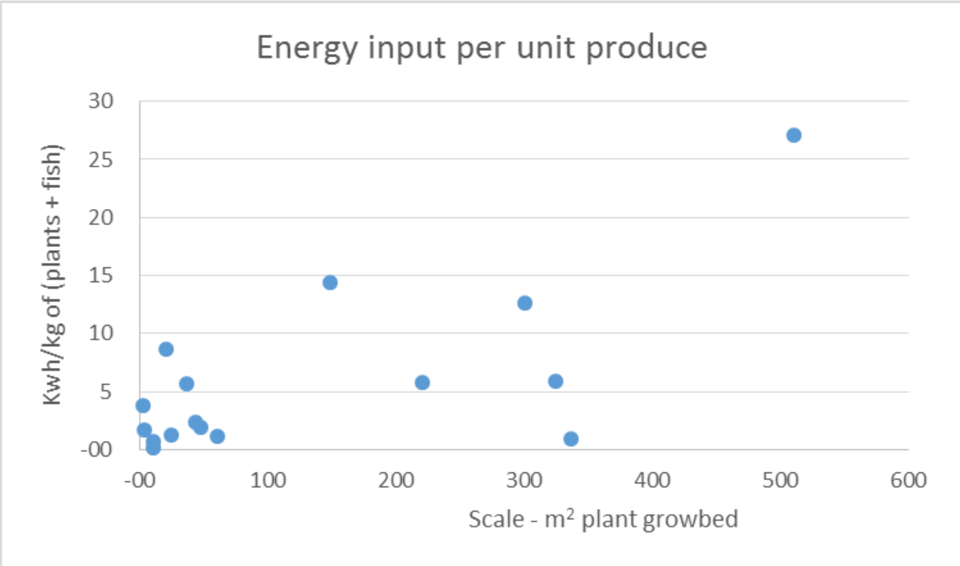
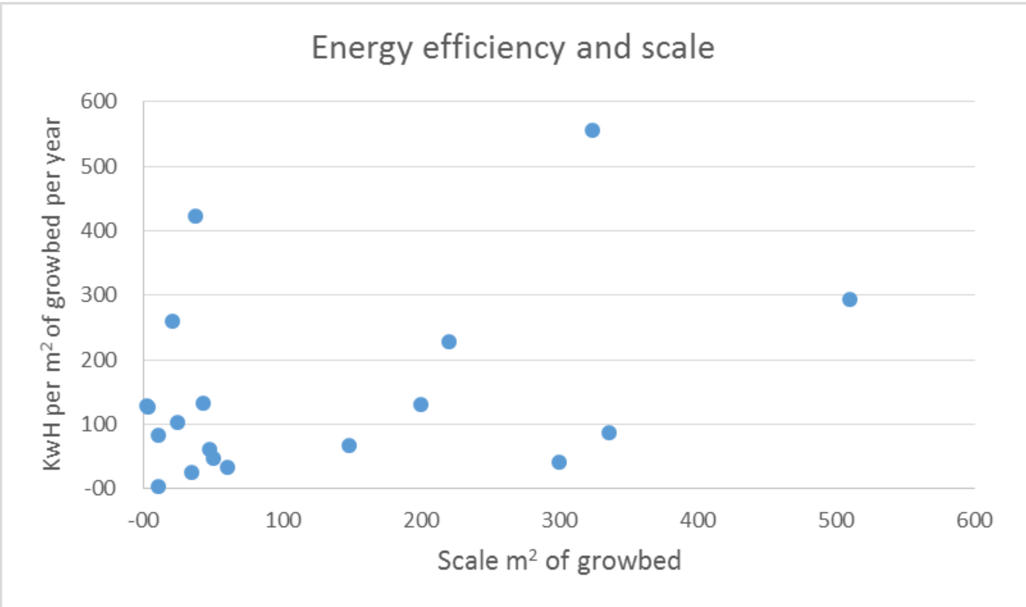


Figure 19: Energy consumption per m^2 growbed area



8.1.9 Working parameters

On the basis of the above analysis the following parameters are assumed for the financial models. Comparison is also made with likely values for these parameters in hydroponic or conventional horticultural systems.

Table 5 : Production parameters for aquaponics and alternative systems

Parameter	Low	Medium (most likely)	High	Hydroponics	Conventional horticulture
Plant: fish production ratio	5:1	15:1	30:1	NA	NA
Plant production kg/m^2/yr	30	40	60	similar	Intensive greenhouse systems around 25% lower. Conventional outdoor systems 4-10 times lower (Resh 2004)
Fish production kg/m^3(fish tanks)/yr	15	50	70	NA	NA
Fish feed per m^2 plant grow-bed g/m^2/day[72]	20	65	100	NA	NA
Plant production kg/m^3 water (system)/yr	100	150	200	likely to be roughly double since no fish tanks	NA
Water consumption % of total volume/day	0.5	2	5	May be significantly lower (as much as 50%), since intensive aeration of fish or growbeds is not required; however, regular dumping of nutrient solution would shift this balance	NA
Water consumption l/kg plant production	20	50	80	May be significantly lower (as much as 50%), since intensive aeration of fish or growbeds is not required (less	Highly dependent on climatic conditions, but may be 10 times higher. However, micro-irrigation

[72] Higher rates based on data from UVI system. Lennard suggests this amount can be reduced to as little as 16g fish feed/m2/day, but this is based on a mathematical model assuming total mineralisation and nutrient uptake in the system

				aeration); however, regular dumping of nutrient solution would shift this balance	systems may reduce this.
Energy use kWh per m^2 of plant growbed	30	80	200	Likely to be significantly lower: lesser need for intensive aeration; less physical head; less complexity in plumbing, resulting in lower head loss.	Depends on degree of automation but conventional horticulture is labour rather than energy intensive
Energy use kWh/kg plant production	1	2	4	Likely to be significantly lower: lesser need for intensive aeration; less physical head; less complexity in plumbing, resulting in lower head loss.	Depends on degree of automation but conventional horticulture is labour rather than energy intensive
Labour use hrs/kg plant production	0.2	0.4	0.8	Lower. Less labour associated with water quality monitoring, fish maintenance, system maintenance	Similar or higher. For organic systems weeding and harvesting is labour intensive. On the other hand less routine maintenance and less skill (expensive) labour required
Iron supplement kg/kg of plant production	0.0125	0.0125	0.0125	Part of standard nutrient mix	Would be supplied if necessary in standard fertilizer
Total capital investment US$/m^2 of plant growout beds[73]	50/500[74]	1000[75]	2000	Considerably lower. No need for fish tanks, blowers, settling tanks etc. Plant system cost similar.	Limited, except for greenhouse systems, but these are rarely used in tropical/sub-tropical environments.

Although the above may be taken as informed estimates of system performance, the preceding analysis reveals the high degree of inconsistency in practice. This in itself is an important characteristic of such systems: performance is rather unpredictable, both within and between systems, making this a highly risky investment. This is not surprising given the management issues reviewed in the previous section.

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[73] This assumes a relatively well serviced Pacific island and import of most technology/equipment
[74] The smaller of these two figures is used to represent a fully homebuilt/diy system using widely available materials
[75] Tokunaga et al estimate $200 for this parameter in their model, which given the data we have analysed appears optimistic. The possible implications of such lower capital costs are discussed further below.

8.2 Model systems

A series of cost of production models based on the above parameters are presented in Annex 5. The output from these models is summarized in table 6. The models are available as separate functional spreadsheet models that may be used to estimate production costs according to both assumed design/production parameters, and local input costs (such as energy and labour).

In terms of input costs the main variation will be in the cost of labour, which is taken as US$7/hr in the baseline. Power costs are also likely to vary between islands and may be as high as $0.8/kWh (double the baseline) in some locations. Power costs can be reduced by using solar, but this will substantially increase upfront investment costs, and therefore also financial risk.

Generating power from diesel fuel on a small scale (or use of diesel or petrol pumps) will typically require 0.3 to 0.4 litres of fuel per kWh, and costs can be assessed accordingly. In European countries fuel cost are typically 0.9 to 1.8/l at the pump, or perhaps 70% of that for commercial fuel oil. Prices are likely to be 1.5-$2/l in many Pacific Island countries, corresponding to $0.6-0.8/kWh.

Table 6: Production cost estimates for different systems $/kg (vegetable or fish) [76]

Cost/kg of combined fish/veg production US$/kg	Pessimistic/ poorly run	Most likely – good realistic performance	Operating at maximum efficiency and performance
Small scale back yard (home built)	16	11	6
Small scale back yard (purchased as kit)	27	17	9
Family business	29	13	8
SME type business	22	9	5
Medium-large scale fully commercial enterprise	18	7	4

This analysis suggests that well run large scale commercial systems may be able to produce vegetables (such as lettuce, bok choy) for a minimum of around $6-$8/kg. If the lower capital costs as estimated by Tokunaga et al (2013) are used instead in the baseline, this brings production costs for medium-large scale enterprise down to around $4-5/kg[77]. Smaller scale

[76] Based on following input prices typical of some Pacific Islands: Labour $7/hr; electricity $0.5/kWh; fish feed at 0.8-$1/kg

[77] Unfortunately it is not possible to undertake a complete comparison of these costs with the Hawaii study, but the limited figures presented so far suggests that they are generally at the optimistic end of the range that we have used.

commercial systems would struggle to produce for less than $10-14/kg, and back yard producers – if they were to cost all inputs realistically – are unlikely to be able to produce for less than $8-20/kg (the latter if a complete commercial good quality “off the shelf” system is purchased) although perhaps the most dedicated, using a home built system might mange $5-6/kg

The baseline itself may be regarded as relatively optimistic, in so far as it assumes no extended learning or lead in period, and no serious disruption related to pests, system failure, market seasonality etc. The reality is likely to be up to 2 years learning and adapting during which time operating losses will be made that should be added to capital costs.

The two extremes are unlikely since these assume pessimistic or optimistic values across all five major production parameters (fish yield, plant yield, energy use, labour use and capital costs) and some of these are likely to be inversely related.

8.3 Other studies

A study is currently underway at the University of Hawaii on the economics of commercial aquaponics in Hawaii. Unfortunately the full text is not yet available but a summary of findings to date is available on the news site[78]. The study concludes that (in Hawaii) “commercial scale aquaponics is economically feasible and profitable to some degree”. Broadly speaking the preliminary figures they present suggest something closer to the optimistic model used here, rather than the baseline. They also note that organic certification makes a significant difference to profitability.

[78] http://www.ctsa.org/index.php/news/economics_of_commercial_aquaponics_in_hawaii.

9 STRENGTHS AND WEAKNESSES OF AQUAPONIC PRODUCTION COMPARED WITH ALTERNATIVE PRODUCTION METHODS

9.1 Flexibility of location and proximity to markets

Hydroponics, recirculated aquaculture and aquaponics all require less water than conventional production systems and no soil. They can therefore be done in urban areas (and closer to markets); in soil-less or infertile areas; and in arid or saline areas.

In such situations they may be the only - or at least the most cost effective - way to grow fish and/or vegetables. This does not mean they will be the most economically efficient way to *source* vegetables or fish. In many cases it will still be cheaper to import them to an area which is not suitable for conventional fish or vegetable production.

9.2 Efficiency of water use

Both recirculating aquaculture systems and hydroponics require less water than conventional aquaculture and horticulture systems. Water consumption in recirculated aquaculture has been estimated at 0.5-1.4 m^3/kg fish production compared with 3 to 30 m^3/kg fish production in traditional pond or more intensive raceway aquaculture[79]. Aquaponic and hydroponic production systems use around 10% of that required in conventional horticulture, and aquaponics may be slightly better than hydroponics in so far as periodic (e.g. every 6 weeks) dumping of system water is a normal feature of optimal hydroponic production to prevent build-up of pathogens and to maintain optimal nutrient concentrations.

If the objective is primarily fish production with minimum water use, the addition of plants will be a disadvantage, increasing overall levels of evaporation/transpiration and water use. If the objective is primarily plant production with minimal water use, the inclusion of fish in the production system is likely to marginally decrease water use efficiency because of losses related to intensive aeration and associated evaporation in the fish production unit. However – as noted above – this may be more than compensated by the lack of periodic system water dumping in aquaponic systems – which is a common feature of hydroponic systems.

9.3 Use of space

Plant yields (production/space) of hydroponic and aquaponic systems are at least double those from conventional horticulture (from 1 kg/m^2 in soil to 2.3 kg m^2 in soilless for lettuce; from 1.2-2.4 kg/m^2 in soil to 14-74 kg m^2 in soilless for tomato[80]).

Fish yields per unit area or volume from recirculating aquaculture systems and aquaponics are higher than for more extensive aquaculture production in ponds, but similar to yields achieved in through flow systems on land or cages in rivers, lakes and sea.

[79] Verdegem et al., 2006 op cit
[80] Resh 2004 op cit

9.4 Growth rates

Growth rates of plants are likely to be higher in aquaponic and hydroponic compared with conventional horticulture systems. This relates to the managed nutrient concentrations and the greater exposure to air. Higher growth rates reduce cropping cycle and improves cash flow.

Comparison between aquaponic and hydroponic systems is more complex. The concentrations of nutrients in aquaponic systems are substantially lower than those found to be optimal in hydroponics, and the ratio of some of the nutrients is also sub-optimal. Without appropriate nutrient supplementation therefore, growth rates will generally be lower in aquaponic compared with hydroponic systems. This is not always the case however, and very good performance is often found in aquaponic systems, possibly related to the complex bacterial and fungal flora which may enhance nutrient uptake by plants and suppress certain diseases.

For some plants, and in particular for fruiting vegetables, the inability in aquaponic systems to adjust nutrient concentrations in real time to take account of different requirements at different growth stages is a significant weakness compared with hydroponics.

In enclosed systems (building/greenhouse) plants may suffer from high humidity associated with fish tanks. Aquaponics may compromise standard temperature and humidity controls used in greenhouses, but this is unlikely to be a problem in tropical/sub-tropical systems.

9.5 Growth and food conversion rate of fish

Basic biological production parameters for fish – growth rate, stocking density, food conversion ratio – are likely to be similar in aquaponic and conventional aquaculture systems[81] [82]. These may be enhanced through temperature controlled environments (inside buildings or greenhouses) in high latitudes, but this adds substantially to capital costs and is not of relevance to most situations in Pacific islands.

9.6 Cost structure

Production costs in aquaponic systems will normally be higher than those for hydroponic systems, and significantly higher than those for conventional horticulture unless there is a significant charge for water use. Fish production costs are likely to be similar to, or higher than those for fish culture in recirculated aquaculture systems (because optimisation is more difficult), and substantially higher than those for conventional pond, raceway or cage culture.

9.6.1 Capital outlay

The level of investment depends on both scale and sophistication of technology. The simplest aquaponic and hydroponic systems can be home built at low cost, using for example 55gallon drums, but may be subject to high labour/operating costs per unit production because of the

[81] See for example Pantanella et al., 2012a, DeLong et al. 2009; De Graaf and Janssen, 1996; Degani et al,1988
[82] See for example Seawright et al., 1998; Al-Hafedh et al., 2008, Pantanella et al., 2012a; Endut et al, 2010; Pantazis and Neofitou, 2002; Ahmad, 2008

need for regular checking, higher risk of loss because of limited backup, and relatively inefficient small scale pumps.

The most sophisticated systems will operate more controlled environments and have back-up of all important components (blowers, pumps, automatic timers, valves etc.) as well as sophisticated monitoring and alarm systems.

Either way, aquaponics systems are more complex, require additional components and – like for like - are bound to be more expensive than equivalent hydroponic or recirculated aquaculture systems.

9.6.2 Operating characteristics and costs

Aquaponic systems require more energy for pumping and aeration than hydroponic systems because of the requirement for deeper grow-beds, more intensive and continuous aeration (to meet the needs of both fish and plants), more complex pipework, and in some cases additional filters. While these costs may be reduced significantly through good design and use of solar or other renewable energies it will always remain a comparative weakness. They are even higher when compared with conventional horticulture systems.

Labour costs associated with the fish production are likely to be similar between aquaponic and recirculated aquaculture systems, but substantially higher than those associated with medium-large scale intensive pond, tank and cage culture systems which are now highly labour efficient.

Labour costs associated with plant production in aquaponic systems are likely to be higher than those required in hydroponic systems, because of the higher costs of pest control in aquaponic systems, and increased labour demands associated with system complexity and maintenance. Labour costs in hydroponic systems are likely to be lower than those associated with conventional horticulture because of the lower requirement for weeding. We are unable to comment definitively on labour costs in aquaponic v conventional horticulture, but it seems likely that the higher costs associated with pest management may be compensated by the lower costs associated with weeding.

Other costs – seed, pots, general equipment - are likely to be broadly similar.

9.6.3 Fixed and variable costs

Perhaps the biggest single disadvantage of aquaponics systems from a financial point of view are the high fixed costs. Not only are capital costs high compared to other systems, but basic operating costs – in particular power and a significant proportion of labour - are also relatively inflexible and do not vary with output. Thus even when production is low – for example as a result of disease, nutrient deficiency, temperature – the system must still be kept running, seedlings prepared, and high energy and labour costs continue to be incurred. This contrasts with other systems where the main cost (usually labour) can be varied according to demand (weeding, harvesting etc.).

The implications of this are that production cost is highly dependent on production rate, and if high rates are not achieved, for whatever reason, production cost (or losses) will increase very rapidly. This is illustrated graphically in the models which show that if, for example, only 50% of target production is achieved (which is not unlikely) productions costs soar.

9.7 Marketing characteristics

9.7.1 Species flexibility

The choice of both fish and plant species is more limited in in aquaponic systems compared with stand-alone hydroponic or recirculated aquaculture systems. This is because some plants do less well in some aquaponic systems, especially those with demanding or life cycle related nutrient requirements. Equally some fish species have more demanding water quality requirements and will not thrive in nutrient concentrations suited to plants.

9.7.2 Plant:fish ratio

Because of the basic biological parameters discussed in previous sections, most aquaponic systems are dominated by plants in terms of production area, production weight and revenue. As such fish tends to be a side product, and in many more commercial systems is managed specifically as a nutrient generator the plants, rather than as a product in its own right. Fish can be produced in relatively larger quantities, but this will require additional investment in settling and water treatment to take care of the increased waste generated over and above that which can be absorbed by the plants.

In the case of the former production strategy, fish is simply being used as an organic nutrient generator, and are effectively an input cost to the business – something which is openly conceded by some of the more commercial producers. The sustainability rationale for this is discussed further below. In the case of the latter production strategy, the whole rationale for integration (i.e. the plants use the waste nutrients from the fish) is partially compromised.

If a true balance is sought – i.e. maximising nutrient uptake by a combination of fish and plants – then the producer must live with a constant challenge of maintaining the biological balance in the system while at the same time producing what the customer requires. This represents a significant management and marketing challenge. It is notable that most of the larger producers have abandoned this strategy.

The problem is especially significant for small to medium scale producers, and especially when seeking to supply small to medium scale markets. Output cannot easily be adjusted to market demand – or if it is for one product, there may be an excess or shortage of the other product. This applies not just to overall quantity, but also to seasonality. An aquaponic system must run on a stable stock of both fish and plants in the correct ratio (appropriate to the system) to maintain water quality suitable for both. If there is a strongly seasonal market it will be difficult to vary output in line with demand without adjustments to the other component or a breakdown in system balance.

9.7.3 Product quality and safety

Product quality from aquaponic systems is widely regarded as high, based mainly on its “organic” reputation. It is unclear at the present time whether full organic certification will be possible in some countries (this has always been difficult for hydroponics simply because it is soil-less), but clearly an organically certified fish feed (which are significantly more expensive than mainstream feeds) would be required. Nonetheless, many producers have been able to generate a market premium associated with the quality and/or novelty of the product, and especially its “sustainability” credentials.

Aquaponically grown vegetables in systems using very high quality fish feeds have also been shown to be high in many desirable micro-nutrients (e.g. anti-oxidants, manganese, zinc)[83]

However there are some significant issues relating to entry into mainstream markets. There is a perceived risk of contamination due to use of water with coliforms from fish. Proper management and handling should however allow for compliance with safety standards. Furthermore there are no *E.coli* risks due to the cold blooded characteristics of fish. Nonetheless, in some countries (notably the US) aquaponically grown fish will usually automatically fail third party food safety audits under USDA guidelines, due to the basic characteristic of growing fish in recycled un-composted faecal and metabolic wastes (poop)[84].

By way of contrast, hydroponics is well known for the ease with which relatively sterile and bacteria free conditions can be maintained.

9.8 Skills and management demands

Aquaponics is considerably more demanding than horticulture, hydroponics or even recirculating aquaculture. It requires not only an understanding of fish and plant husbandry but also of water chemistry. Although the requisite skills and knowledge can be developed to some degree “on the job” there is little doubt that a good grounding in biology would help address the unexpected; and the unexpected will occur.

On top of these husbandry skills, management of an aquaponic system will require substantial organisational competence. Planning and scheduling production to maximise capacity utilisation and thereby minimise unit production costs will be the greatest challenge. But this in turn must be adjusted as necessary to meet market demand, seasonal variation and customer requirements.

There is also a requirement for a level of commitment and dedication far higher than that required in more extensive conventional production systems. For example, monitoring water quality may reveal a spike in ammonia or nitrite concentrations due to excessive feeding or malfunction of treatment systems. This would require immediate partial water change and/or cessation of feeding of fish and probably intensive aeration. Even for a small system this implies substantial commitment.

9.9 Risk and uncertainty

9.9.1 General

The most likely and optimistic models shown above and presented in more detail in Annex 5 assume production systems in continual production, with fairly efficient use of time and space, restocking following harvesting, and limited downtime. In reality this is unlikely to be achieved, or at least not for several years. For example, bolting is a relatively common phenomenon, and pests may be particularly problematic at certain times of year. Because of the relatively high fixed costs any downtime is costly, and this implies substantial financial risk. This is illustrated graphically in Figure 20 using figures generated by the baseline model.

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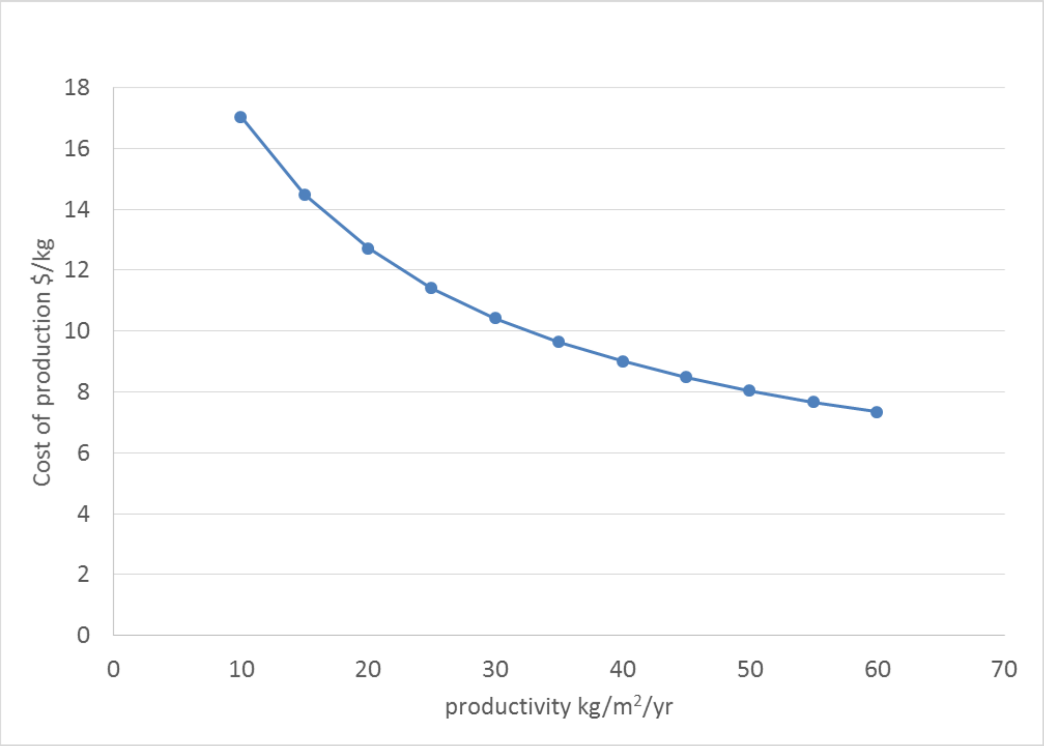
[83] Bright, L. 2013. Aquaponics for Community Benefits. SPC Aquaculture Expert Consultation 23 – 27 September 2013. Rarotonga, Cook Islands
[84] Fox, B. 2013 op cit

Failure to meet target production rates (typically around 40kg/m^2/yr) may result from a range of different factors that affect aquaponic systems, and to a lesser extent hydroponic and recirculated aquaculture systems. These include failure or malfunction of pumps, aeration, and filtration systems; loss of power; nutrient deficiencies; bolting; spoilage and wastage; and pest and disease.

The integration implicit in aquaponic systems effectively compounds these risks and may constrain response, especially with respect to pest and disease treatment. Furthermore, any significant failure of an aquaponic system may require a complete restart, which requires 4-8 weeks to "settle" the system and achieve adequate steady nutrient concentrations. Some hydroponic systems (notably raft and media based systems) are rather less risky than others (water supply failure is less critical) but remain susceptible in the medium term.

Risk can be reduced through greater levels of investment in monitoring and backup and/or increased levels of dedicated husbandry.

Figure 20: Relationship between plant production rate and cost of production (base model)



9.9.2 Disease

There is some uncertainty about the relative incidence of disease in aquaponic compared with hydroponic systems. Aquaponic systems are rich in beneficial bacteria and fungi, and there is some evidence that these make the system less prone to root diseases. If disease does break out however, response is constrained by the need to conserve that same complex bacterial and fungal flora (which is essential also for nitrification), and also to protect the fish. Many disease treatments – including some of those used in organic horticulture, will damage the microfauna and flora and in some cases kill the fish. Equally, some of the treatments for fish disease may damage the microfauna and flora or affect the health of the plants.

There is also some evidence that aquaponically grown vegetables are more prone to fungal leaf diseases because of high humidity, though this is probably less of a problem in more open systems likely to be used in the Pacific.

Hydroponics on the other hand relies on maintaining a relatively sterile system (indeed this is an oft quoted advantage of hydroponic systems), but as with aquaponics, the density of planting is bound to increase vulnerability to some pests. For good or ill however, hydroponic producers are free to use a much wider range of pest and disease treatments, or undertake complete cleanout and sterilisation, and the threat from pests and disease may therefore, overall, be regarded as lower than in aquaponic systems.

Relative to conventional horticulture systems, hydroponic systems have fewer problems from soil borne diseases and pests. However, if they are in greenhouses, there may be excessive humidity which favours fungal diseases. In more open systems (e.g. using shade netting) then aphids and other insects may thrive in the relatively sheltered and plant rich environment. The balance between these factors will depend on location and system.

Intensive recirculated aquaculture systems are also vulnerable to disease, but can be kept bio-secure more easily than extensive systems. Adding an extensive vegetable production system makes biosecurity for the fish significantly more difficult.

9.10 Sustainability

9.10.1 Waste utilisation and nutrient utilization

The primary rationale for aquaponics (as oppose to hydroponics) is to use or minimise waste nutrients from intensive aquaculture, and to exploit the synergies between fish and plant production. However plants are inadequate as the sole form of waste treatment, and most aquaponics systems need solids settling, biofiltration and degassing systems to remove excess solid waste and/or to convert nutrients to a form suitable for plants. The plants serve as the final polisher (known as secondary treatment) in this system. The proportion of waste nutrient actually used by the plants is therefore highly variable depending on the efficiency of solids settling/removal and removal of nutrients by bacteria in the system. By way of example, researchers at CTHAR[85] in Hawaii have shown that in some of their systems, of total nitrogen input into the system as feed, about 27% is captured as fish flesh, 43% is captured as lettuce biomass, and the balance is lost as nitrogen gas or as solids removed from the system and used to fertilize garden plants. Where the proportion of nutrients consumed is high (i.e. efficient waste reduction), the ratio of plant to fish production will also be correspondingly high.

As things stand, and for those systems where the objective is primarily plant production (which is most near commercial systems) it is unclear that conversion of 40-50% of the very high quality nutrients in fish feed into plant matter is a sensible or sustainable use of resources. Furthermore, there have been concerns for many years about the sustainability of high quality fish feeds themselves, derived as they are in large part from fish meal, the resources for which are under intense fishing pressure in many countries. This may be addressed through the use of high quality organic pellets, but the cost of these will be high in most Pacific island nations.

To maintain the rationale and enhance sustainability, some practitioners use home grown organic feed such as worms produced in compost. While this may be more logical from a

[85] College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa

sustainability perspective, it makes the system yet more complex and interdependent, and management becomes correspondingly more demanding to maintain system balance and stability.

9.10.2 Energy use

Most aquaponic systems are energy intensive and are significantly worse in this regard than hydroponic or conventional horticulture, especially in the tropics.

9.10.3 Dependency on the wider economy/imports/exports

Aquaponics is sometimes promoted as a route to food security and food independence. This is hard to justify. Aquaponics depends on a range of inputs that would have to be imported to most Pacific islands: high quality fish feed, seed, analytical kits, pumps, blowers, solar energy kits etc

9.10.4 Exotic species

Most growers are encouraged to use exotic species, and in particular Tilapia because of its far superior qualities in aquaponic systems. Introduction of this species or others particularly suited to aquaponic systems to many islands may be undesirable from an ecological perspective and may not be sanctioned by some governments.

9.10.5 Water use

Relative water use efficiency (i.e. water consumption per unit production) has been addressed in section 9.2. It will be higher or lower in aquaponic versus hydroponic systems depending on the intensity of aeration in aquaponic systems, and the frequency of nutrient solution dumping in hydroponic systems. Both will be more water efficient (ca 10x) than conventional horticulture.

9.11 Summary

A comprehensive colour coded summary of strengths and weaknesses of aquaponics compared with alternatives is presented in Annex 6. Red corresponds to a relative weakness and green to a relative strength with intermediate colours as appropriate. This analysis is summarized, using qualitative scores in lieu of colours in the charts (Figures 21-23) below.

It is immediately clear that from almost all perspectives, the weaknesses of aquaponics outweigh the strengths. It is costly, risky, demanding, and not especially sustainable according to a range of criteria. By far the most significant strength – efficiency of water used – is also shared by most hydroponic systems, and possibly also by some micro-irrigation systems. It is clear therefore that for most Pacific island nations hydroponics and/or conventional aquaculture (especially marine cage or shellfish culture) conducted as independent activities are most likely to meet market and economic needs.

Figure 10: Comparative efficiency of resource use (high score =more efficient)

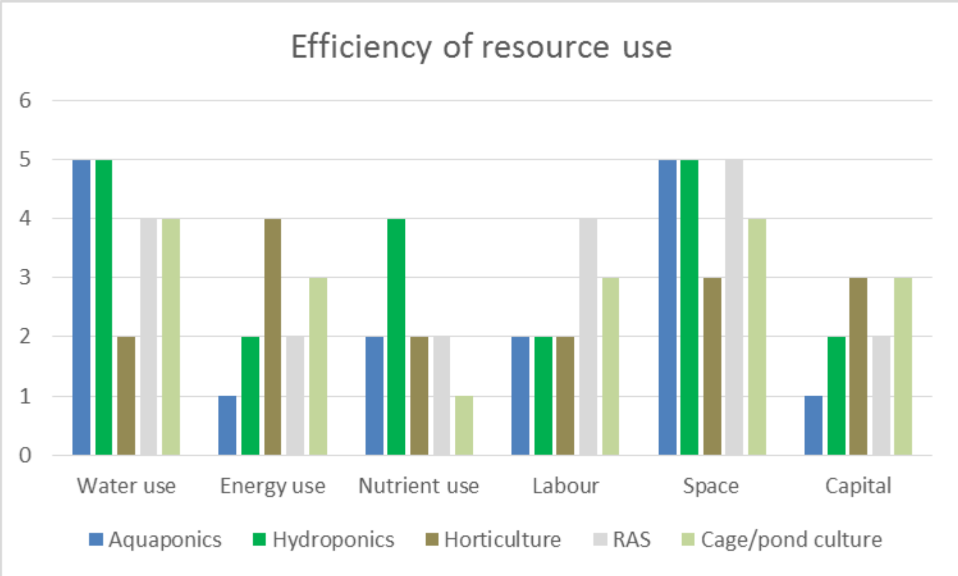


Figure 11: Demands in terms of knowledge, skills, commitment.

High score = relatively more demanding

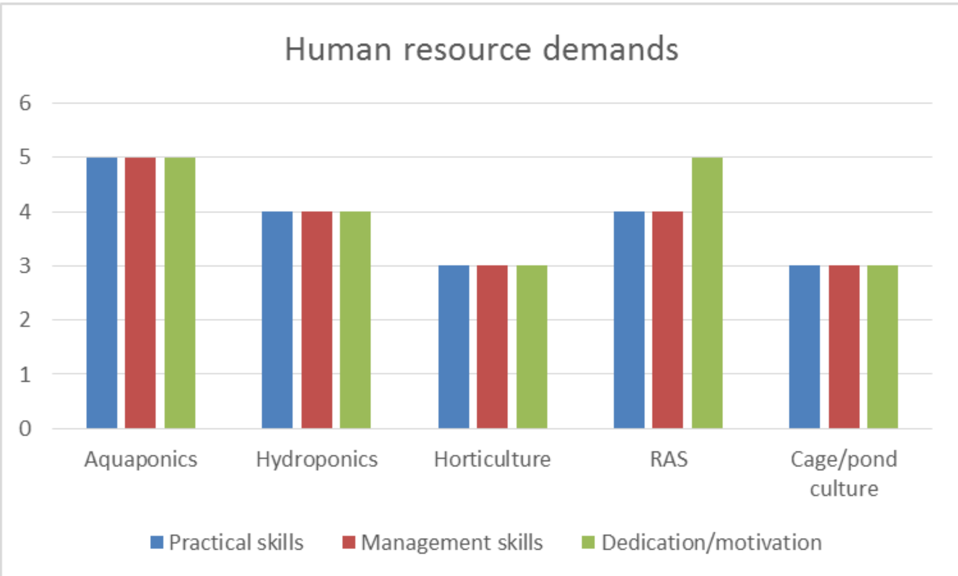
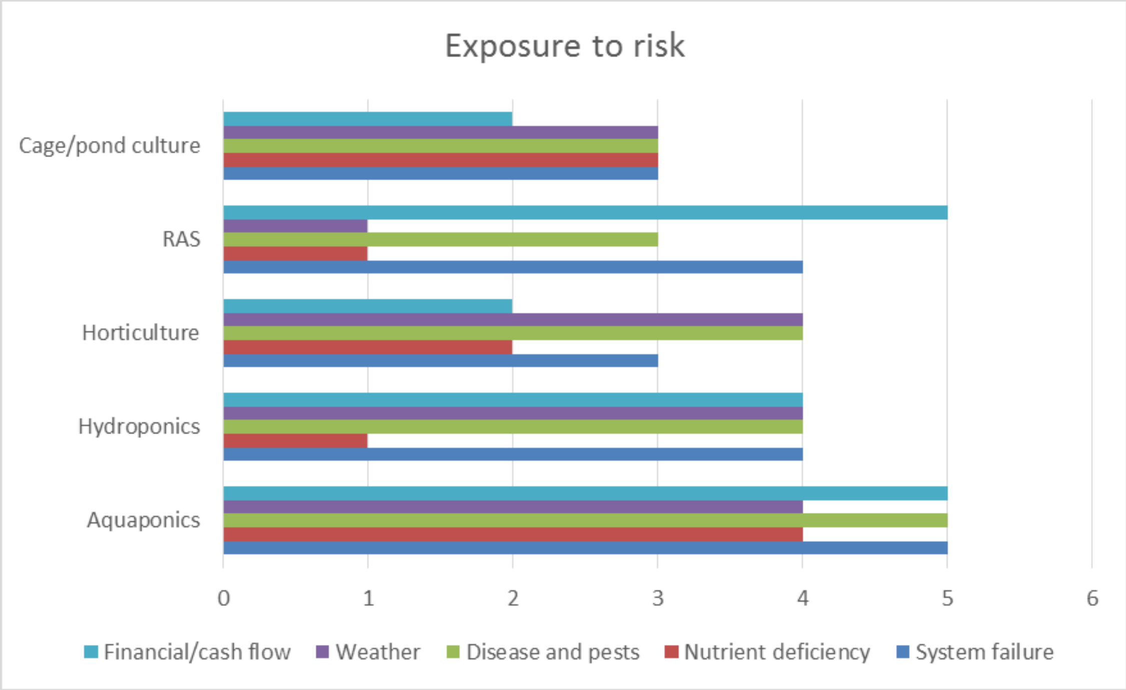


Figure 12: Exposure to a range of risk factors - high score = greater exposure



10 CONCLUSIONS

Aquaponics is a seductive concept which is especially appealing to those seeking to promote more sustainable food production systems. It involves the production of both fish and vegetables, using a single nutrient source – fish feed – and ensures that most of the wastes that would normally be released from intensive fish culture are instead used to grow vegetables. It is important to recognise however that aquaponic systems are primarily *vegetable production systems*, simply because of the biological nature of the relationship between fish nutrient production and plant nutrient uptake. Intensively grown fish produce a lot of nutrients, the consumption of which requires a large amount of plant production. This is particularly the case if part of the enterprise objective is to minimise solid waste disposal to the environment. In several of the more commercial systems operating at the present time, the fish are regarded as “organic nutrient generators”, rather than as an important product in their own right.

The primary advantage of aquaponics, shared with some forms of hydroponics, is water use efficiency. Other oft-cited advantages include nutrient utilization efficiency, product quality and food security. These latter are undermined to some degree by the use of high quality high protein (usually fishmeal based) fish feed as nutrient source in the more efficient and productive systems, and/or the need to add nutritional supplements.

A further possible advantage lies in the complex organic nature of the aquaponic nutrient solution compared with the relatively simple chemical based solutions used in hydroponics. There is some evidence to suggest that this has pro-biotic properties, promoting nutrient uptake, protecting against some disease, improving product flavour and extending shelf life.

Against these advantages must be set significant disadvantages, especially from a business or enterprise perspective. Integrating recirculating aquaculture with hydroponic plant production increases complexity, compounds risk, compromises system optimisation for either product, restricts management responses – especially in relation to pest, disease and water quality - and constrains marketing. Energy use is relatively high because of the need for both aeration and pumping in most systems. Capital and fixed operating costs are also high, increasing financial exposure should production fail to reach design targets. System failure may result in a two month restart and rebalancing period. Given that most aquaponic systems are dominated by plant production this is a heavy price to pay.

Aid agencies should be extremely cautious about supporting aquaponics initiatives, and should undertake thorough local feasibility studies before investing in any demonstration systems or support programmes. Such assessments should consider carefully whether aquaponics in a particular location will have any real advantages over hydroponics and/or stand-alone aquaculture production systems (or indeed fisheries) as a means of generating high quality food in water and soil deficient islands; and whether the skills, knowledge and dedication are available to sustain viable aquaponics. In any case, given the complexity of the systems it is arguable that aquaculture and/or hydroponic systems should be introduced first, and if successful may be combined with the other component at a later date, if local physical and economic conditions favour such integration.

10.1 Conditions for success

Conditions for success are demanding and limiting. They include:

1. **A scarcity of soil and/or water.** Aquaponics cannot compete with conventional forms of production in environments which are favourable to those production systems – i.e. ready access to land and water – unless it is part of some wider business or attraction to which it contributes interest, novelty or credibility.
2. **The capacity to finance a long start up and learning phase.** No amount of expert guidance or operational manuals will preclude the need for such a phase, because every system will have slightly different bacterial flora and water chemistry characteristics, and these characteristics will vary according to season, system maturity, plant species used and so forth.
3. **Dedication and commitment.** Producers must be prepared to be on hand at all times (or employ near permanent staff) to respond to any type of system failure.
4. **Strong organisational skills.** In order to cover the relatively high fixed costs, producers will need to be highly organised in terms of planning and scheduling production, and balancing fish and plant production.
5. **Strong marketing skills**. In most cases the product will be more expensive than that produced from hydroponics or alternative aquaculture systems. A niche premium market will be needed to survive. Furthermore, if fish is also to be regarded as a commercial product both fish and plant outlets will need to be developed or cultivated, and significant time spent ensuring that demand is appropriate to the quantities of fish and vegetables produced.
6. **Innovation and determination to address problems associated with pests**. Those with many years practical experience flag up pest management as possibly the greatest challenge for aquaponics producers.

10.2 Opportunities for development

Notwithstanding the demanding conditions set down above, there may be opportunities for specific kinds of aquaponics initiatives in some locations, so long as the key features and risks associated with these systems are fully understood at the outset.

1. **Small-medium scale vertically integrated production/restaurant/retail/resort**. In Europe and the US the most successful aquaponics ventures are those where the aquaponic venture is combined with other "visitor attractions" and/or an organic/ local produce shop and/or café or restaurant. The Pacific version of this model might be an aquaponics café/shop in or close to significant urban and tourism centres and/or aquaponics directly linked to a resort, especially on water deficient islands where fresh vegetables are difficult to source. In this case the resort or café fully understands the production limitations and risks, but exploits the intuitive appeal of aquaponic systems. Staff are also likely to be permanently on hand to deal with routine care and maintenance of such systems at limited marginal cost. Again this might be done with either hydroponics or aquaponics but the tourist appeal of the latter is likely to be greater.
2. **Education and social development in small institutions.** In so far as an aquaponic system is a microcosm of a freshwater (potentially marine) ecosystem, and illustrates many of the essential processes of life and "ecosystem services", it serves as an excellent

educational and skills development tool. The complexity of management and the requirements for dedicated husbandry and significant planning and organisational skills – while being a disadvantage from a commercial perspective – may be considered an advantage when seeking to strengthen communities, team work, and responsibility. As such, the development of aquaponic systems in schools, communities, prisons, military camps etc. may meet a range of other needs while at the same time generating some healthy locally produced food. Again the rationale and opportunity for this will be greater in water and soil deficient islands. There is however a significant risk that such systems will nonetheless break down once the initial flush of enthusiasm is over, and without a strong commercial incentive to maintain efficient production. The absence of a determined "champion", limited access to high quality cheap fish food, and high costs of electricity are also likely to be a significant constraints on longer term success.

3. **Household scale production** may have some potential in water/soil deficient islands, or where people are sufficiently wealthy that investment in backyard gardening becomes a worthwhile hobby activity in its own right. Relatively simple "two bucket" backyard designs may be fairly robust and resilient, so long as feed inputs are kept below some basic operating thresholds, and so long as Tilapia (or possibly catfish) are available. The main constraint here will be energy cost and energy/equipment reliability. Operating costs may be reduced through investment in solar panels/wind turbines and batteries, and reliability can be addressed through investment in monitoring systems and backup. In most cases however small scale *hydroponic* systems are likely to serve this need better at least in the first instance. These may be upgraded to aquaponic systems once skills have been developed, and if there is demand for fish and a ready supply of high quality fish feed and seed.

10.3 The way forward

The focus of aid agencies and development NGOs should not be on the promotion of aquaponics per se; rather on raising awareness of the range of options available to enable vegetable (and in some cases fish) production in water and soil deficient islands, and facilitation of local initiatives aimed at overcoming these constraints.

To date, aquaponics has been primarily pursued by aquaculturists through aquaculture/fisheries agents, despite the fact that it is primarily a horticultural activity. There needs to be a rebalancing of effort and support, primarily through agricultural training and extension, but also through joint initiatives of fisheries and agriculture services where appropriate.

If demonstration projects are to be supported, they should be through agricultural and fisheries training/extension/advisory services, and should demonstrate and evaluate objectively a range of conventional and innovative technical responses to local physical and market conditions and needs.

To date integration has been promoted as a "good thing", almost as an article of faith. It is essential that in future the disadvantages of integration – at least in the current economic and marketing climate – are also fully understood.

10.4 Towards an assessment framework

An assessment framework is required to appraise the potential and application of any food production system in the Pacific Islands, and in this regard aquaponics is no different from any others (except for the highly effective marketing and promotion of the idea which has led to it being considered in isolation). Any rigorous assessment framework must appraise the various options available against local conditions and development criteria. In the case of aquaponics, this means primarily assessing its strengths and weaknesses relative to alternatives in that particular context.

Key questions that should be posed before investing in aquaponic production, or in research, development and demonstration, include the following:

1. Is there strong demand for leafy vegetables and modest quantities of fish at a relatively high price? (in excess of US$6/kg farm gate)
2. Is that market readily (economically) accessible from the production site?
3. Does water or soil availability seriously constrain conventional vegetable and fish production throughout the year (note that if local vegetable or fish supply is seasonal, hydroponics or conventional aquaculture are more flexible)
4. Are aquaponic systems likely to be more cost effective than alternative vegetable production systems (such as hydroponics, conventional horticulture or aquaculture) in terms of supplying the target market, taking into account product requirements/specifications, seasonality, water efficiency, species opportunities?
5. Is there a premium on organic and/or sustainably produced vegetables?

If the answer to all these questions is positive, then it may be appropriate to make a more detailed assessment of economic viability of aquaponics at the site. Key issues to address in such assessment, in addition to routine cost and revenue estimates, would be:

1. How do the risks of failure compare with more conventional vegetable production systems (assuming these are possible) in the location?
    - *For example* would the system have less disease, more stable temperatures, more reliable water?
2. Do we have skilled and committed full time labour to maintain the operation and/or the financial resources to install alarm systems, backup power etc?

Cost and revenue estimates must be realistic and take account in particular of lost production due to bolting, disease and occasional nutrient deficiency; and wastage due to occasional market surplus.

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ANNEX 1: CONSULTEES

The following provided information or advice through face to face discussions, or via email/telephone. Additional information was provided by others (many of whom remained anonymous) through the online survey (Annex 2)

Name	Organisation
Rebecca Bainbridge	UK Aquaponics
Phil and Rowena Mansfield	Herbs from Wales, UK
Alis Ballance	Moffat CAN Scotland (community based aquaponics initiative)
James J Godsil	Sweet water organics, Sweet water Foundation, Indo-American Aquaponics Institute, Milwaukee, USA
Wilson Lennard	Aquaponic Solutions, Australia
Don Grant	Tasman Bay Herbs, New Zealand
Zac Hosler	Living Aquaponics, Big Island, Hawaii
Tim Mann	Friendly Aquaponics, Inc., Honoka’a, Hawaii (aquaponics production and training)
Tim Pickering	Secretariat of Pacific Community, Inland Aquaculture Specialist
Avinash Singh	IACT Aquaculture Officer, Suva, Fiji
Lynsay Rongokea	Rarotonga Aquaponics Demonstration Project, Cook Islands
Colin Mills	Oasis Hydroponics, Raratonga, Cook Islands
Larry and Patty Yonashiro	Aquaponics No Ka ‘Oi, Kahului, Maui, Hawaii
Clyde Tamaru	Aquaculture specialist, College of Tropical Agriculture and Human Resources (CTHAR), University of Hawai’i at Manoa
Bradley (kai) Fox	College of Tropical Agriculture and Human Resources (CTHAR), University of Hawai’i at Manoa
Leinaala Bright	Hawaiian Herbal Medicine Cabinet, Waimanalo, Hawaii
Michael Ogo	Aquaculture Specialist, Northern Marianas College (Research, Extension and Education Service)
Mari Marutani	Western Pacific Tropical Research Center, University of Guam
Shalendra Kumar Singh	SPC Fiji
Maria Sesilia Luamanuvae	Senior Fishery Officer, Samoa
Marc Andre Lafille	DRM French Polynesia
Latu Tuiano	Fishery Officer, Tonga
Fialua Monise	Research Officer Tuvalu
Viliame Fakava	FAO, Samoa
Ben Ponia	Secretary, MMR, Cook Islands

ANNEX 2: FISH AND PLANT SPECIES USED IN AQUAPONIC SYSTEMS

Type of Fish	Lower Temperature Limit (°C)	Optimum Temperature (°C)	Upper Temperature Limit (°C)
Freshwater			
Bluegill	14.4	20.6	23.9
Brook Trout	6.7	14.4	21.1
Brown Trout	6.7	15.6	23.9
Channel Catfish	12.8	29.4	
Coho Salmon	6.7	12.2	15.6
Lake Trout	5.6	12.8	
Largemouth Bass	10.0	21.1	29.4
Muskellunge	12.8	17.2	22.2
Northern Pike	13.3	17.2	23.3
Rainbow Trout	6.7	16.1	23.9
Smallmouth Bass	15.6	18.3	22.8
Walleye	10.0	19.4	24.4
Tilapia	20	27-30	
Barramundi	20	26-30	
Common carp		18-25	
Snakeskin gourami		22–30	
Snakehead		20-26	
Machrobrachium		28-31	

Plant species	optimal temperature range (day) (°C)	optimal temperature range (night) (°C)	minimal temp for growth (°C)
Fennel	15-25		5
Parsley	20-26		8
Sweet basil	20-25	20°C (13-18°C with basal heating)	12
Lettuce	17-28	3-12°C for head formation	
tomato	22-27	13-15 (for fruit setting)	8-10
sweet pepper	22-28	15-18 (for fruit setting)	10-12
eggplant	22-26	15-18	9-10
watermelon	21-26	15-18	12
melon	25-30	18-20	12
cucumber	24-28 (21 at root level	18-20	10-13
zucchini squash	24-30	15-18	10-12
bean	21-25	16-18	12-14
pea	15-18 (no more than :	15-18	4
strawberry	18-22	10-13	6
cabbage	15-18		5
Chinese cabbage	18-20	15	
radish	15-18		5
chard	16-24		5
spinach	10-15 (max 25)		5
leek	15-25		
carrot	20-27		6
celery	15-18		

ANNEX 3 NUTRIENT CONCENTRATIONS IN AQUAPONIC AND HYDROPONIC SYSTEMS

Table 3.1: Water parameters in the University of Virgin Island (UVI) aquaponic system

Physical parameters	pH	70-7.5
	$CaCO_3$ (alkalinity) (mg L^{-1})	113 (>100)
	Dissolved oxygen (mg L^{-1})	≥5
	Total suspended solids (TSS) (mg L^{-1})	13 (4-32)
	Total Dissolved Solids (TDS) (mg L^{-1})	236-550 (1000-1500)
	EC (mS cm^{-1})	0.5 (<4.00)
	BOD (mg L^{-1})	< 20
Macronutrients (mg L^{-1})	NO_3-N	26.3 - 42
	Total Ammonia Nitrogen (TAN)	0.95-2.2
	Total Phosphorus	8.2-16.4
	Orthophosphate	15.0
	K	44-63.5
	Ca	11.9-24.2
	Mg	6.0-6.5
	SO_4	18.3
Micronutrients (mg L^{-1})	Cl	11.5
	Fe	1.3 –2.5
	Mn	0.06 – 0.8
	Zn	0.34-0.44
	Cu	0.03 –0.05
	B	0.09-0.19
	Mo	0.01

Rakocy *et al*. (1992, 2004a, 2004b, 2006)

Table 3.2 - Optimal nutrient concentrations for mineral in a standard solution (mg L^{-1})

	Min	**Optimal**	**Max**
Nitrate nitrogen ($N - NO_3$)	40	60-160	200
Ammonia nitrogen ($N - NH_4$)		0-40	100
Phosphorus (P)	15	30-90	130
Potassium (K)	100	200-400	600
Calcium (Ca)	75	150-400	600
Magnesium (Mg)	25	25-75	150
Sulfur (S)	50	75-300	600
Choride (Cl)			600
Sodium (Na)			400
Iron (Fe)		2-4	10
Boron (B)		0.2-1	5
Manganese (Mn)		0.2-2	15
Copper (Cu)		0.01-1	5
Zinc (Zn)		0.01-1	20

(Massantini, 1968)

ANNEX 4: PRELIMINARY REPORT ON SURVEY

Purpose

This short report provides an overview of the survey reports so far obtained. It is designed to provide an accessible introduction to our survey results rather than as any kind of formal analysis.

Design and distribution of the structured survey.

This structured survey is an important research tool as it acts as a portal to case studies and semi-stuctured interviews, as well as producing information in its own right. It was crucial to find a reliable and cost effective method to design and distribute the survey and www.survey.monkey.com was chosen. Initial survey design was structured around the draft questionnare and check-list described in Annex 1 of the original project proposal. Following a pilot survey, some changes were made. The mailing list was developed from web-based research and personal contacts. A covering email included the weblink to the survey and a brief explanation of the purpose of the research, the identity of the client and the confidential nature of the replies. The survey was sent in small email groups by geographical area to avoid the type of mass mailing that can be rejected as spam, and was first distributed on 12th August 2013.

TABLE 4. MAILING LIST BY GEOGRAPHICAL AREA AND ESTIMATED ACTIVITY. (UPDATED)

Region	Commercial (in intent)	Community Initiative	Research/ Academic	Total
Pacific, Asia, Australasia	5	1	6	**12**
North America	24	6	2	**32**
Europe	6	3	16	**25**
Baltic	1	0	4	**5**
UK	4	5	4	**13**
Total	**40**	**15**	**31**	**87**

NB. These catagories are of necessity somewhat approximate. There is a certain amount of cross-over, and some of the “commercial” interests may be selling equipment rather than running a commercial aquaponics operation, and/or may not be profitable. Other “commercial” operations may be running e.g. a cafe which uses the aquaponics operation as a point of interest rather than a commercial operation in its own right.

There were eight responses to this first request. The survey was sent to the same addresses again on 21st August 2013, as a thank you and as a reminder to those who had not yet completed it. A later mailshot covered four likely companies in Hawaii. This all generated a further 19 replies, and more may be yet to come. Respondents used whatever units they wished to complete the survey but all have been converted to metric measurements for ease of comparison.

The first four responses on the survey website are our own comments for the pilot survey, and are disregarded.

Data protection

Data protection and respondent privacy has been carefully considered. Survey respondents contact details are confidential unless released with the express written or emailed permission of the respondent. For the final report, results will be dissaggregated and detailed case studies or individual stories only described with permission. In this interim report, which is not intended for publication, individual cases are described but not identified, and insufficient detail is given to identify individual respondents. Emails were sent from a business email address belonging to one of the consultants (using the BCC field to ensure privacy) and are only held as a list on that address. They will not be passed to a third party. Survey Monkey does not hold the email list. Such guarantees are essential as a common courtesy and to encourage participation in the survey.

Respondents are here identified only by the number assigned to them by the survey software, whose records are on a password and only accessible to the consultancy team. Where full contact details have been provided this gives us the means and the permission to contact this person again.

Overall comments

There was a heartening thirty responses, with many full and frank survey answers and a great variety of situations described. Slightly over half of the respondents had research involvement, and about one third also described themselves as commercial, and another third as semi-commercial. Over half the responses were from northern Europe. These responses do not initially lend themselves to averaging, and much would be lost by so doing. Quick pen pictures follow, as a guide to who might be suitable for a telephone interview and to give a flavour of the responses.

Individual responses to structured survey

#5 South Pacific.
Time taken 10 mins. Full contact details provided.
A college enterprise, growing Tilapia on a flowthrough set-up, with plans to incorporate aquaponics as a demonstration uni. Little detail as yet.

#6 Baltic
Time taken 13 mins. Full contact details provided.
A researcher who is **planning** to add a drip-irrigated plant unit to a small aquarium. Currently keeping common carp in a recirculation system with aerator and bio-filter. Views aquaponics as a niche in the industrial world and believes it important to use local fish and plant species.

#7 Northern Europe
Time taken 15 mins. No contact details provided.

A researcher who also ticked the "fully commercial" box. With three tonnes of fish annually, a 600m^2 greenhouse, 12,000 m^3 water and nearly 400m^2 of plants this is a fairly substantial set-up. Tilapia are kept at 70kg/m^3 with aerator, drum filter and bio-filter. Plants (herbs and leafy veg) are grown in pots on hydroponic plant tables, producing ten to twelve tonnes annually, all year round.

#8 Indian Ocean

Time taken 24 mins. Full contact details provided

A research aquaculture centre describing a sizeable **past** operation. They had an enterprise covering some 500m^2 with 20m^3 for tilapia, 200m^2 for plants and 60m^3 of water. All under shade netting. The fish were in four tanks, each of five cubic metres, at 30-40kg/m^{3,} producing nearly two tonnes annually. It was a pumped recirculation system with aeration, settling tank and biofilter. Herbs and leafy veg were grown all year round on floating rafts, producing about 2000 plants every month. Power use was about 3kW/hr all year round, labour 20 hours a week. Fish food was 32% protein with a feed conversion ratio (FCR) of 1.7. Annual inputs included 10,000 seedlings and 6,000 fish at 40g each. Some fertiliser was bought in for the plants (KOH and Fe).

#9 Area unknown.

Time taken 36 seconds. No contact details given.

Respondent went through the survey but declined to fill in any of it.

#10 North America

Time taken 36 mins. No contact details given.

This is a "fully commercial" unit in a 460m^2 greenhouse with two fish rooms. Six fish tanks each of 4.5m^3 each hold about three hundred 0.9-1.3kg tilapia, with another seven 0.4m^3 tanks for fingerlings and associated filtration tanks. There is a total of 230m^3 growing beds and about 120m^3 of water. It is a recirculation system with pumps, aeration and a settling tank. This unit produces about 700 heads of lettuce each week, all grown from seed. The fish are not tracked. No fertiliser is bought in, just fish food: 2700kg a year for the mature fish and a few bags for the fingerlings, which come in at 0.5g each. Aquaponics was reckoned to be the future, and likely to get bigger and better. The respondent reckoned that there were "way too many chemicals in the food we eat". Labour is one very busy person, power use is "too much" and after five years the unit has yet to make a profit.

#11 Northern Europe

Time taken 12 mins. Full contact details given.

A researcher running a two-centre urban enterprise on rooftops in a city. Each greenhouse is 250-300 m^3 with 12m^3 total fish tanks and 220m^2 plants. Tilapia, sturgeon, perch and ornamentals are stocked at between 10 and 80 kg/m^3, producing 150kg/m^3 pa. These are pumped recirculated systems with aeration, drumfilter and biofilter. Herbs and all types of salad are grown all year round on floating rafts and in communal troughs (NFT channels?). Production is about 5T/pa. Power use is a constant 2kW, labour 60 hrs/week and fish food is TilapiaVegi, a 38% protein vegetable only feed, 1T/pa. FCR is stated at 1.3. They buy in plants and seeds, and 1500 fish at 10g. Our respondent considers this all needs intelligence, good planning, alarm systems, proper tools and a shed. He likes the stability and quality of the system and considers that the future is very bright. Further financial information is provided.

<u>#12 USA (south)</u>

Time taken 8 mins. No contact details.

This is a small demonstation unit of 150 m^2 with 2.0m^3 fish tanks, 14.0m^3 water and 50m^2 of plants. Tilapia and koi are stocked at 12.5kg/m^3 water, and the unit produces 18kg fish pa from 36kg fish food. Production is year round; a range of plants but no production figures. Labour is highly variable, fertiliser use is minimal, few seeds and 100 fingerlings a year. It's a low-cost system. They wish the tanks were bigger. They see the future of aquaponics as good but more commercialised than this.

<u>#13 Northern Europe</u>

Time taken 27 mins. Full contact details provided.

This is a research/pilot/demonstration scheme in a greenhouse using passive solar energy. It's a small system; 1000L fish tanks, 2700L water and 10m^2 plants. Tilapia, trout, catfish, sturgeon and comon carp are stocked at a maximum of 40kg/1000L producing 40k fish annually. It is a recirculation system with a variety of plants and fruit on ebb and flow irrigation. They produce about 200kg of plants every year, all year round without heating. Fish feed is about 60 kg annually. They would like a unit ten times bigger. Energy efficiency is good; it is only needed for the pump and for aeration.

<u>#14 Northern Europe</u>

Time taken 14 mins. No contact details.

This is a semi-commercial operation using 40 “zip grow” towers in a greenhouse. 2000L water, 150kg tilapia annually and about 500kg of plants. It's a pumped recirculting system with a settling tank and biofilter. A variety of plants are grown with drip irrigation. There are pests, an iron deficiency and a lack of fruit in fruiting crops. It takes 18 hours week a week, 150kg fish food annually, thousands of seeds and 300 fish brought in annually at 150g each. Our respondent considers that this business needs careful planning, scale and crop rotation, and sees the future as variable, divided between commercial high density techniques and small scale enterprises. Some financial information has been provided.

<u>#15 USA (South)</u>

Time taken 29 mins. Full contact details given.

This is a sizeable fully commercial research and training orgaisation. The site is one third of an acre, with 45m^3 of fish tank and 500m^2 of troughs, producing 545kg fish pa. FCR is 1.52, worked out with some precision. They grow everything. They wrote the book on pest control in aquaponics. They see the future as bright but consider that there are a lot of dodgy consultants out there.

<u>#16 Northern Europe</u>

Time taken 12 mins No contact details.

Respondent has no current involvement in aquaponics but **<u>used</u>** to keep tilapia in a greenhouse recirculation system.

<u>#17 Northern Europe.</u>

Time taken 21 minutes. Full contact details.

This is a medium sized demonstration and research system on 100m^2 with tomatoes in a greenhouse and perch in artificial ponds (?outside). The system holds 20000L, plant area is 64m^2 and fish density is 20 kg/m^3. They produce 320kg fish and 2500kg tomatoes annually. It takes 20 hours a week. They wish they had a drum filter instead of a settling tank and consider that the main factor is the fish price.

#18 USA (North)

Time taken 5 mins No contact details.

This is a community pilot/demonstration on 185m^2 with 38m^3 tanks. It is a greenhouse system, recirc with a biofilter, 140m^2 of plants and shade netting. Very little other information provided.

#19 Northern Europe

Time taken over one week. No contact details.

This is a "fully commercial" gourmet food production company that also does installations, consultancy courses and outside catering, according to the survey response. The site is 1000m^2 and getting bigger. They have 40,000L of fish tanks, 71,000L water and 300m^2 plants under polytunnels and shade netting. They keep trout, perch, common carp and brook trout in below ground tanks. They stock at 20kg/1000L and produce 1T fish annually. It's a pumped recirc system with aerator, settling tank and bio-filter, with herbs, leafy veg and salad grown in various media. They go for seasonal produce only but it is planted and harvested all year round. Power use is 35 kW/day, labour 60 hours a week, 1,100kg fish food annually, FCR 1.1:1 (?????). They buy in seeds, fingerlings and various types of fertiliser. No other information.

#20 Northern Europe

Time taken 12 mins. Full contact details provided.

This is a funding call for 50k Euros to install a 150 m^2 aquaponics demonstration using ornamental fish in a greenhouse. This respondent skipped the question about past experience.

#21 Northern Europe

Time taken 27 mins. Full contact details provided.

This is a research pilot/demo/semi-commercial community project of 170 m^2, with 8 m^3 fish tanks, 25 m^3 water and 70 m^2 of plants. It produces four to five tonnes of plants annually, grown using the nutrient film technique. It produces all the year round, mainly tomatoes (1T annually) and uses 5T commercial trout pellets at 36% protein. The electricity is provided by photovoltaic cells. FCR is 1.1:2. They have their own trout hatchery, so don't need to buy in fish, just tomato plants. They do buy in a phosphoric acid and essential mineral fertiliser mix. They would like a bigger demo system to convince others that this might run successfully. Crucially, they have separated out the fish and the plants into two recirculation systems, optimising production in both. They see a prosperous future for aquaculture.

#22. Southern Europe

Time taken 8 mins. Some contact details.

This is a tiny pilot/demonstration. 3 m^3. 700L for tilapia, 300L plants. It's indoors, on an ebb and flow system with no sunlight. They see a bright future for aquaponics.

#23 N Europe and USA (North)
Time taken 2 mins.   No contact details.
Answers inconsistent. ? Ignore.

#24 No contact details and no responses. 45 seconds, ignore.

#25. Northern Europe
Time spent 51 mins, email address given.
Involved in a **past** research/demo/community project working on cold water aquaponics. It was 600 m^2 with 50 m^3 total fish tanks, 160m^3 of water and 50 m^2 of plants, half in a greenhouse and half in a building. Trout were kept, at 60 kg/m^3, producing 6300kg annually. It was a recirc system with herbs and leafy veg on floating rafts, producing all the year round. Our respondent reckoned you need faith, money , good friends, reliable labour and a knowledge of biology and fisheries. The system was good for renewing resources, as a money maker and for safe food production, in their opinion. Sees the future as small local units for local markets.

#26 UK
Time spent: unknown but considerable.   Full contact details given and much communication already.
This is a commercial operation covering roughly 320 m^2 and uses 35m^3 of water, plus rainwater holding tanks of 8,400 L. Plants cover approx 150m^2. Some is in two buildings, some under shade netting. They grow trout, perch, mirror carp and common carp in a variety of sizes of polyethylene tanks and two breeze block ponds. They sell 300-400 trout annually. It's a fairly complex recirculation system. Plants (all from seed) are brassicas, herbs and water cress, both inside and outside. They use parasitic insects to control pests, being wary of poisoning the fish. Fish can be harvested all year round but no plant harvesting is done in January or February; it's just too cold. Electricity costs about £1500 annually, and fish food about £400. Two people work 30 hours a week each just to keep and maintain the systems. The fish eat Skretting Trout Elite, a high protein feed. They don't measure FCR but the fish grow very big.

#27 Central Europe
Time spent 48 mins. Full contact details given
A very small (1m2) research unit with two 35L fish tanks and a 35L Hydroton pebble ebb and flow unit. There are catfish, tomato and tobacco plants. The fish were a gift from a fish farm.

#28 Northern Europe
Time spent >one week. Full contact details given
This response is identical to that of #19 but this time there is a little more detail and full contact details are given. This is a UK operation.

#29 Unknown area
Time spent 2 mins. No contact details given
A researcher. No other questions answered and no contact details given.

#30 Southern Europe

Time spent 4 mins. No contact details given.

This is a researcher workng on a 12m^2 plot with a 6L fishtank. Ornamental fish in artificial ponds ad a greenhouse. No other details.

#31 Northern Europe

Time spent 13 mins. No contact details given.

This is a "fully commercial" set-up run by a respondent with a PhD on RAS effluent reuse. There are two small units, 20m^2 and 40m^{2,} There is a total of about 4 m^3 of fish tanks and 50m^2 of plants. One of the two greenhouses has passive solar heating. It is a pumped recirc system with a bio-filter producing 80-160kg fish annually, tilapia, trout and catfish. A greFish at variety of plants and herbs are grown on an ebb and flow system.

#32 Hawaii.

Time taken 27 mins. Contact details given

This is a large fully commercial system on 370 m^2 with 11 m^3 of fish tanks, producing 180-360 kg veggies a week. It's all on half an acre, with some areas covered with tarps and greenhouse plastic. The fish are tilapia, kept in fibreglass over wood tanks, an expensive solution which would not be chosen again. Stocking rate is currently 58kg/m^3 and they need to be thinned. The focus is on vegetable production, no on the fish. The system works by graity from the fish tank at the top of the system, flowing through the plants and then being pumped back up. There have been many problems ("could write a book"). It takes 60-80 hours a week, 100kg fish food annually, a little Fe, a pH buffer and some seeds. The fish are home-bred. This all needs dedication but it is not such hard work as producing conventionally grown vegetables. It could go very large in the USA if Food Certification Safety issues are sorted out (presumably to do with selling the fish) and is viable in area with decent water and a power source. We should contact this grower; he is inviting us to.

#33 Hawaii

Time taken 15 mins. No contact details given

This is on 3 acres, and is still under development. It is intended to be a fully commercial set-up, with 43 m^3 fish tanks, 6.4 m^3 of water and 280 m^2 plants. The fish are tilapia and catfish, in three big ground tanks of innovative design. Stocking is 12kg/m^3 and plant production is about 544kg monthly. There are various growing system and our respondent provides a detailed description of the water system. There is a good variety of plants. Some pH problems.

#34 Northern Europe

Time taken 40 seconds. No contact details given

Semi-commercial, no other questions answered.

ANNEX 5: FINANCIAL PRODUCTION MODELS

Baseline/most-likely

Parameters and costs	backyard system (min)	backyard system (max)	small business (min)	SME type business (max)	medium scale commercial
total area m2	2	3	45	90	750
area of plant growbeds m2	2	2	30	60	500
volume of fish tank cubic m	1	1	5	15	100
capital cost/m2	300	2,000	800	1,000	800
capital cost (plant) and media	270	2,400	14,400	36,000	240,000
capital cost (equipment)	180	1,600	9,600	24,000	160,000
depreciation rate plant	10	10	10	10	10
depr. rate equip	5	5	5	5	5
labour (hrs/kg production)	1	1	0	0	0
energy (kwh/yr/m2 productior	130	100	80	80	70
food conversion	2	1	1	1	1
iron chelate kg/kg plants	0	0	0	0	0
fish seed pc/kg production	4	4	4	4	4
plant seedlings/kg plant prod	4	4	4	4	4
Plant productivity kg/m2/yr	20	20	30	40	40
Fish productivity kg/m3/yr	15	20	50	50	60
plant production	30	40	900	2,400	20,000
fish production	11	14	250	750	6,000
labour cost/hr	8	8	8	8	8
power cost/kwh	1	1	1	1	1
food costs/kg	1	1	1	1	1
seed cost/pc	0	0	0	0	0
plant seedlngs/pc	0	0	0	0	0
iron C costs/kg	15	15	15	15	15
buffer/kg food					
interest rate	-	-	0	0	0
operating cost					
depreciation plant	27	240	1,440	3,600	24,000
depreciation equip	36	320	1,920	4,800	32,000
interest (on 50% capital)	-	-	600	2,100	14,000
energy	98	100	1,200	2,400	17,500
labour	227	216	3,680	7,560	52,000
feed	19	24	325	810	5,760
fish seed	10	13	234	703	5,625
plant seed	12	16	360	960	8,000
iron	6	8	169	450	3,750
sales/fuel			5,000	5,000	15,000
Total operating cost	434	936	14,928	28,383	177,635
cost of comb. production ($/kg	11	17	13	9	7

Pessimistic

Parameters and costs	backyard system (min)	backyard system (max)	small business (min)	SME type business (max)	medium scale commercial
total area m2	2	3	45	90	750
area of plant growbeds m2	2	2	30	60	500
volume of fish tank cubic m	1	1	5	15	100
capital cost/m2	500	2,000	1,500	2,000	1,500
capital cost (plant) and media	450	2,400	27,000	72,000	450,000
capital cost (equipment)	300	1,600	18,000	48,000	300,000
depreciation rate plant	10	10	10	10	10
depr. rate equip	5	5	5	5	5
labour (hrs/kg production)	1	1	1	1	1
energy (kwh/yr/m2 productior	150	150	200	150	150
food conversion	2	1	1	1	1
iron chelate kg/kg plants	0	0	0	0	0
fish seed pc/kg production	4	4	4	4	4
plant seedlings/kg plant prod	4	4	4	4	4
Plant productivity kg/m2/yr	15	15	20	30	30
Fish productivity kg/m3/yr	15	15	20	20	20
plant production	23	30	600	1,800	15,000
fish production	11	11	100	300	2,000
labour cost/hr	8	8	8	8	8
power cost/kwh	1	1	1	1	1
food costs/kg	1	1	1	1	1
seed cost/pc	0	0	0	0	0
plant seedlngs/pc	0	0	0	0	0
iron C costs/kg	15	15	15	15	15
buffer/kg food					
interest rate	-	-	0	0	0
operating cost					
depreciation plant	45	240	2,700	7,200	45,000
depreciation equip	60	320	3,600	9,600	60,000
interest (on 50% capital)	-	-	1,125	4,200	26,250
energy	113	150	3,000	4,500	37,500
labour	264	324	4,480	13,440	108,800
feed	19	18	130	324	1,920
fish seed	10	10	94	281	1,875
plant seed	9	12	240	720	6,000
iron	4	6	113	338	2,813
sales/fuel			5,000	5,000	15,000
Total operating cost	523	1,079	20,481	45,603	305,158
cost of comb. production ($/kg	16	27	29	22	18

Optimistic

Parameters and costs	backyard system (min)	backyard system (max)	small business (min)	SME type business (max)	medium scale commercial
total area m2	2	3	45	90	750
area of plant growbeds m2	2	2	30	60	500
volume of fish tank cubic m	1	1	5	15	100
capital cost/m2	50	1,000	500	500	400
capital cost (plant) and media	45	1,200	9,000	18,000	120,000
capital cost (equipment)	30	800	6,000	12,000	80,000
depreciation rate plant	10	10	10	10	10
depr. rate equip	5	5	5	5	5
labour (hrs/kg production)	1	0	0	0	0
energy (kwh/yr/m2 productior	60	100	40	35	30
food conversion	2	1	1	1	1
iron chelate kg/kg plants	0	0	0	0	0
fish seed pc/kg production	4	4	4	4	4
plant seedlings/kg plant prod	4	4	4	4	4
Plant productivity kg/m2/yr	30	30	50	60	60
Fish productivity kg/m3/yr	30	30	60	70	70
plant production	45	60	1,500	3,600	30,000
fish production	21	21	300	1,050	7,000
labour cost/hr	8	8	8	8	8
power cost/kwh	1	1	1	1	1
food costs/kg	1	1	1	1	1
seed cost/pc	0	0	0	0	0
plant seedlngs/pc	0	0	0	0	0
iron C costs/kg	15	15	15	15	15
buffer/kg food					
interest rate	-	-	0	0	0
operating cost					
depreciation plant	5	120	900	1,800	12,000
depreciation equip	6	160	1,200	2,400	16,000
interest (on 50% capital)	-	-	375	1,050	7,000
energy	45	100	600	1,050	7,500
labour	264	259	4,320	7,440	59,200
feed	38	35	390	1,134	6,720
fish seed	20	20	281	984	6,563
plant seed	18	24	600	1,440	12,000
iron	8	11	281	675	5,625
sales/fuel			5,000	5,000	15,000
Total operating cost	403	729	13,948	22,973	147,608
cost of comb. production ($/kg)	6	9	8	5	4

ANNEX 6: STRENGTHS AND WEAKNESSES OF ALTERNATIVE PRODUCTION SYSTEMS AGAINST DIFFERENT CRITERIA

Dark green = efficient/desirable; light green = fairly efficient/desirable; buff = neutral; pink = not efficient; red = inefficient/undesirable

Characteris-tic	Aquaponics	Hydroponics	Conventional horticulture	Recirculating aquaculture	Other forms of aquaculture
Efficiency and sustainability					
Water	High. 20-80l/kg production	High. Some hydroponic technologies may be more water efficient because less evaporation (less aeration). However most hydroponic operators periodically dump nutrient solution which will reduce water use efficiency	Low. Requires 10 to 50 times more water. However there are intermediate micro-irrigation systems that are close to hydroponics/aquaponics?	High However, intensive aeration is accompanied by significant evaporation. Oxygen injection systems can be highly water efficient	Generally high Cage aquaculture arguably uses no water, in so far as it does not change the area of water subject to evaporation. Pond aquaculture consumes relatively little, especially if the pond is in any case a form of water storage
Energy	Low. Takes between 1 and 5kWh/kg production in a well-run system and considerably higher in most	Low to high. Conventional aquaponics is energy intensive because of the need to pump water. However most operate using NFT which achieves aeration with little power consumption. Furthermore no aeration is required to support fish	Variable to good. Greenhouse production in northern and temperate countries may be energy intensive; horticulture in tropical and sub-tropical zones tends to be energy efficient	Low. Takes significant energy to supply oxygen to fish through conventional blowers, though there are more efficient (but capital intensive) alternatives	Cage culture generally consume little power/kg of production, since no aeration is required. Main power costs relate to accessing cages and highly site dependent. Extensive pond culture requires very little energy, but intensive aquaculture typically employs intensive aeration associated with energy costs close to those required in recirculating systems

Feed or fertilizer	Fish capture about 27%, and plants 43% of nitrogen – total 70%. However, nitrogen in fish feed is largely in form of very high quality protein (usually fish-meal based), so efficiency of use of protein resource is doubtful in systems aimed primarily at plant production	Nutrient capture in recycled aquaponic systems is high – probably 50-80% though figures are hard to find. The cost of nitrogen from fertilizer is significantly lower than the cost of nitrogen from fish feed. However, periodic dumping of system water+nutrients represents a significant local environmental pressure if not well managed	Nutrient capture in conventional horticulture is lower than in aquaponics and hydroponics because of dispersal and adsorbtion of nutients on soil particles and organic matter. However, in more organic systems, source of nutrients may be more sustainable than either hydroponics or aquaponics	Nutrient capture in recirculation aquaculture in similar to the fish component in aquaponics – ie 20-30%. A significant proportion of the balance is typically removed in form of solids and may be used in horticulture. The balance is released back to the atmosphere.	Nutrient capture in cage culture is again similar to RAS. In this case the balance is released directly to the wider environment. Intensive pond systems also generate large quanities of high nutrient waste. Some extensive polyculture systems however are highly nutrient efficient
Labour	Aquaponic systems are labour intensive – 0.2-0.8 hrs/kg of production – primarily related to planting, inspecting and harvesting, with additional labour associated with ater quality monitoring fish feeding and husbandry	Hydroponic systems are labour intensive, but likely to be somewhat less so than aquaponic systems, since less labour associated with water quality monitoring, and none related to fish husbandry and assocated equipment maintenance	Conventional horticulture is labour intensive, and probably similar to or slightly greater than hydroponics. Less work is associated with system maintenance but more work associated with weeding, especially in organic systems	RAS are moderately labour intensive, but highly scale and technology dependent	Cage and pond aquaculture are moderately labour intensive, but probably less than RAS except at very large scale
Space	High 2-4 times conventional horticulture	High 2-4 times conventional horticulture	Medium Quite variable, though ell managed intensive soil based horticulture can get close to hydroponics	High	Cage aquaculture systems are highly space efficient Pond aquaculture systems vary from space efficient to space inefficient
Capital investment					

Overall Cost of Production[86]	US$7-10/kg (plants) for a successful and efficient system	US$4-7 (estimate) for an efficiently run system	US$3-5 (estimate for an efficiently run plot)	US$2.5-$6	US1.5-$6/kg
Organisational and institutional issues					
Technical and management skills	Very demanding: system monitoring and adaptation; production scheduling, plants and fish; dealing with pests	Fairly demanding: production scheduling; pests; nutrient and environment	Less demanding – maximising production less critical (lower investment costs) scheduling less critical; pest management more or less demanding	Demanding. Optimal production highly sensitive to water chemistry and efficient stock management	Highly variable
Dedication/motivation	Very demanding – continuous surveillance/ability to respond required	Fairly demanding. Monitoring and rapid response also required	Monitoring and speed of response less critical	Very demanding – continuous surveillance/ability to respond required	Highly variable
Risk					
Potential for and consequences of system failure	Very high. Fish may die; plants may die; fish may be stressed; plants may be stressed; system restart and routine production may take 6 weeks or more. Risks may be reduced by substantial investment in monitoring and backup equipment	Moderate to high. Plants may die. However system restart can be rapid with no requirement to build up stocks in balance.	Subject to normal agricultural risks of drought and pest, though in intensive horticulture these can usually be dealt with	High, but system less complex and restart/restocking can be more rapid.	Generally low, but increasing with intensity
Potential loss of optimal nutrient environment	Nutrient concentrations are determined by the needs and metabolism of fish, plants and bacteria. These can be managed to some extent but	Hydroponics allows for highly controlled and optimal nutrient environments that can be adjusted according to	Nutrient management to optimise productivity is a routine part of conventional horticulture, though partly	NA	NA

[86] Assumes in all cases efficiently run system without system failure, pest or disease

	may be sub-optimal for some species some of the time	plant species, growth stage and seasonality	constrained by soil characteristics		
Vunerability to disease and pests	This is an intensive organic system – as such vulnerable to pest problems, especially in the more open systems used in tropical and sub-tropical zones, but also more difficult to treat. A complex probiotic environment may serve as partial mitigation and enhance nutrient uptake. Threats to system as a whole compounded by potential for both or either fish and plant diseases	Also intensive and also vulnerable to pest and disease, but more treatment options are available, system cleanout and restocking is easier, and system restocking and restart more rapid	Similar to hydroponics but may be better/worse according to local conditions. However. system sterilisation and restocking is more difficult	Mixed. Vulnerability to disease in intensive systems is high, but biosecurity and system sterilisation (eg ozone, UV) typically allows for isolation from disease	Mixed Usually less intensive and more open hence lower disease threat, but more difficult to keep out and treat
Vulnerability to weather	Depends on location and system. Physical cover may be vulnerable to wind; lack of cover may increase vulnerability of plants to wind and extremes of temperature Arguably worse than hydroponics because some fish may be more susceptible to temperature	Similar to aquaponics, but only one type of organism at risk	Similar to hydroponics	Low Fully controlled environment	Mixed Cage culture buffered against temperature change but vulnerable to waves and physical damage; pond culture vulnerable to temperature fluctuation, drought etc
Financial risk	High fixed overhead costs (capital, energy and part of labour) mean that production below design rates will have high impact on unit production cost, and financial losses will build up rapidly	Similar to aquaponics but slightly lower ratio of fixed to variable costs and operation at maximum capacity easier and quicker to re-establish after any kind of shock or loss of productivity	Fixed:variable cost ratio significantly lower and therefore less vulnerable to temporary or longer term losses of productivity	High fixed overhead costs (capital, energy and part of labour) mean that production below design rates will have high impact on unit production cost, and financial losses will build up rapidly	Fixed:variable cost ratio significantly lower and therefore less vulnerable to temporary or longer term losses of productivity

Markets					
Product quality and marketability	Mixed Vegetables possibly better tasting, and can be sold as sustainable (though in reality this may be questioned) Possible problem of fish grown in poo in the dark	Low-medium. Some doubt about quality and taste of hydroponic products (watery?), and not usually organic	Can be high. Taste and quality may be soil dependent. Organic is an option	Product quality can be excellent but production image (growing fish in silos) not good.	Mixed Can be high but some consumer mistrust of more intensive systems
Flexibility to respond to market needs	Low. Very difficult to significantly or rapidly change species mix, or temporarily halt or increase production rate	Medium. Easier to shift species and change stocking levels to suit market needs, seasonalty etc. Possible to shut down seasonally if necessary, though costly idle plant	High. Can stop and start production more or less at will, and costs of operating under capacity are lower	Limited Possible, but costly to change production rate in the short term, but can expand relatively easily in medium term	Lower overheads means rate of production can be changed more easily to suit market conditions, and in tropical/subtropical countries species can be readily changed to suit market conditions