Flow-through Aquaponics to Improve Water Quality and Generate Income

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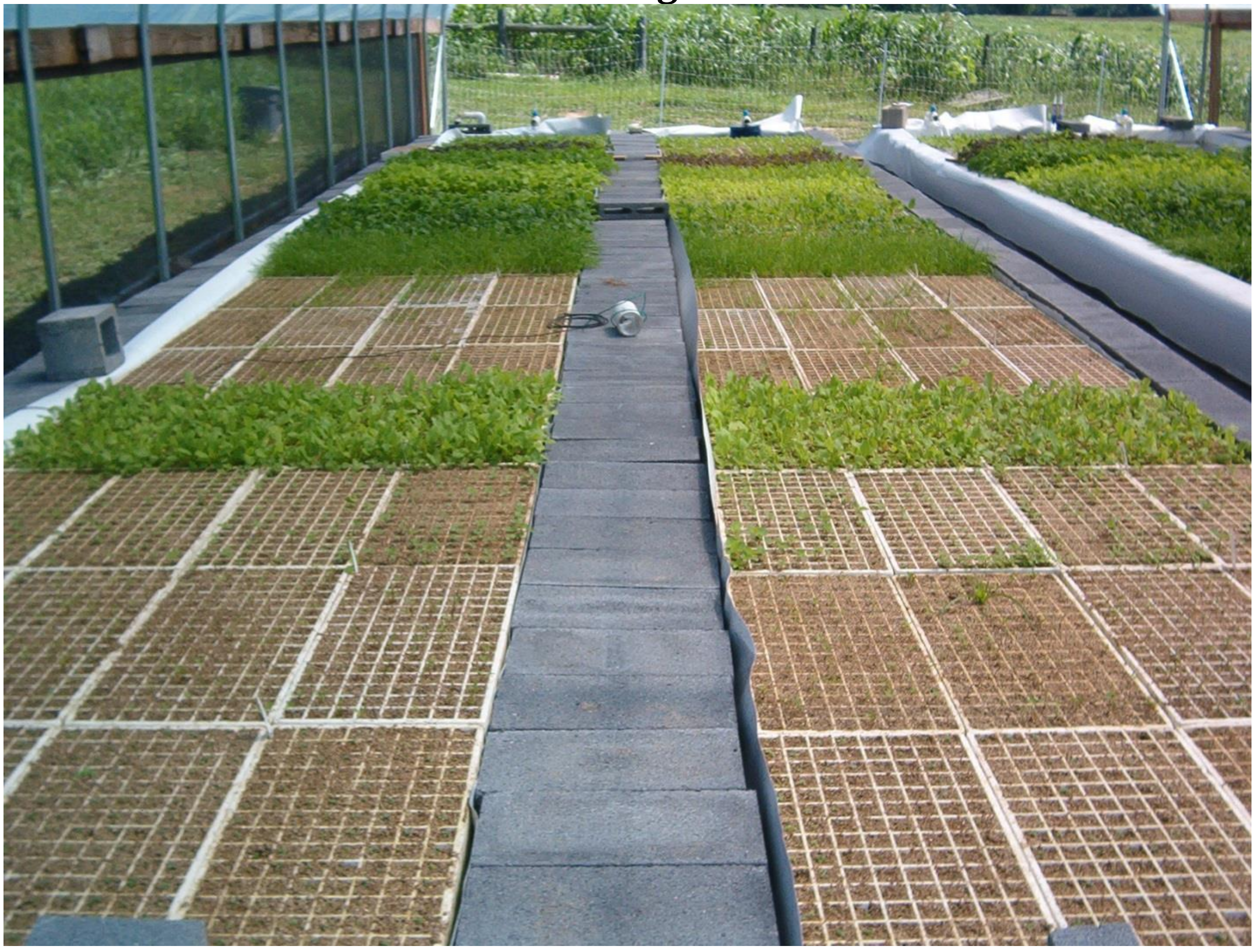


FINAL REPORT

TABLE OF CONTENTS

1. INTRODUCTION 1

2. AQUAPONICS IMPLEMENTATION 2

A. WVU Aquaculture Facility 2

B. Wilson Mill Farms 3

C. Rainbowhead Farm 4

D. Plant Growing Systems 6

E. Water Quality 7

F. Outcomes 9

3. AQUAPONICS WORKSHOPS 9

4. PLANT SCREENING TRIAL 10

A. Stand Establishment 12

B. Harvest Biomass 14

C. Water Quality 18

D. Conclusion 19

5. PROJECT SUMMARY 20

LIST OF FIGURES

Figure 1. WVU Aquaculture Facility with the Fish Building and Aquaponics Greenhouse and High Tunnel labeled………………………………………. 2
Figure 2. Aerial photo of Wilson Mill Farms with the raceway levels labeled (B-F) and the proposed location of the aquaponics high tunnel………………............... 3
Figure 3. Aerial photo of Rainbowhead Farms with the location of the Fish Building and high Tunnel indicated……………………………………………………... 4
Figure 4. Schematic of the screening trial layout………………………………………. 11
Figure 5. Inorganic nutrient (ammonium, nitrate and phosphate) concentrations at the channel influent and the outlets of each of the treatment channels…………….. 18
Figure 6. Total suspended solids concentrations at the influent and outlet of each channel……………………………………………………………………….. 19

LIST OF TABLES

Table 1. Water quality parameters at Reymann Memorial Farm, Wilson Mill Farms and Rainbowhead Farms……………………………………………………………. **7**
Table 2. Mass balance of nitrogen and phosphate availability to aquaponic crops at Rainbowhead Farms……………………………………………………………. 8
Table 3. Stand establishment…………………………………………………………….. 13
Table 4. Harvest biomass………………………………………………………………… 16

EXECUTIVE SUMMARY

The objective of this project was to demonstrate the potential of aquaponics as a low-cost, low tech, sustainable part of a diversified, aquaculture production model. Taking the lessons learned in the design and operation of an aquaponics module at the WVU Aquaculture Facility, we evaluated the potential to implement aquaponics on two existing fish farms. At both it was determined that implementation was feasible. Location and design of an aquaponic system was provided to both producers. Unfortunately one producer withdrew from the project and put his farm up for sale. The second producer had a catastrophic slope failure that threatened his fish production building. Stabilizing the slope and repairing damage to the structure and in-ground plumbing slowed the construction of the aquaponics high tunnel. At this time the high tunnel is partially completed and the farmer is committed to finishing the project.

Two all day workshops were held at the WVU Aquaculture Facility. The workshops covered information regarding fish rearing, aquaponic system design, plant rearing and water quality. A tour of the facility including the fish rearing building, the research aquaponics greenhouse and the aquaponic production high tunnel allowed participants to examine a flow-through aquaponic operation and to ask questions in an informal setting.

A large plant screening trial was done in the production high tunnel. The screening trial had three treatments; low flow, high flow and amended high flow. The low flow treatment delivered effluent at 5 gal/min while the high flow treatment received effluent at 20 gal/min. The amended treatment received 20 gal/min and the vermiculite growing medium was amended with 50% composted fish solids. As the only nutrient source for the aquaponic crops was the raceway effluent, the screening trial manipulated nutrient availability. The low flow treatment received the fewest nutrients while the amended high flow treatment received the most.

A total of 34 cultivars were examined. In keeping with our standard practice, seeds were sown directly into production trays and placed in the aquaponic channels. Stand establishment was quantified 2-4 weeks later. Crops were harvested when they had reached market size. In general, stand establishment exceeded 85% but garlic chive and sage had such poor stand establishment (<15% in at least one treatment) that they were removed from the trial.

Cilantro, salad burnet, parsley, oregano, minutina, and Swiss chard did not exhibit treatment differences in harvest or individual biomass. For all other cultivars, biomass attained in the low flow treatment was the lowest across all treatments. Eight cultivars, including the better performing kohlrabi and bibb lettuce ‘Rex’, attained the greatest biomass under high flow conditions. The remaining 18 cultivars, including all of the mustard greens, and most of the Asian greens, other greens and herbs, grew better in the amended treatment. However, generally the increase in harvest biomass over the high flow treatment was minor. A cost/benefit analysis is required to assess whether the increased effort required to incorporate the fish solids translates into a sufficient increase in harvest biomass to be cost effective. Additional research is necessary into determining the optimum incorporation level for various crops.

The cultivars selected for this experiment comprise a variety of crop types. There were fast growers that matured quickly allowing rapid turnover of growing space but require more labor as they need to be harvested and resown. Another assemblage did not grow as rapidly but have the

potential to be harvested multiple times from one sowing thereby reducing both labor and material costs. Another major group were the herbs, which are a high value crop that can be harvested multiple times but tend to grow more slowly. In addition, within each group of crops there were cultivars that were more productive. These results demonstrate the importance of testing multiple cultivars, where available, to determine which cultivar grows best within a particular system's constraints. Furthermore, this experiment identified cultivars that were not suited to aquaponic production under these conditions.

Flow-through aquaponics has the potential to be more variable in terms of operating conditions because, to a large extent, source water is not modified by the passage through the fish rearing operation, other than an elevation of nutrient concentrations, and therefore the effluent reflects the temperature and chemical signature of the source water. The wide variety of source waters used in aquaculture including springs, well water, lake and stream water that could potentially be used in aquaponic culture, suggests that additional trials should be completed to give a more comprehensive understanding of how well these crops grow in aquaponic systems.

This project provided additional information to fish farmers interested in adding an aquaponic module to their operation. However, we were unable to achieve a major goal of implementing and evaluating aquaponic production at two fish producers. As flow-through fish culturing operations are not standardized, there are numerous options as to how to incorporate aquaponics. This wide variety of options impedes adoption of the practice.

1. Introduction

The purpose of this project was to demonstrate the potential of aquaponics as a low-cost, low tech, sustainable part of a diversified, aquaculture production model. Aquaponics is the integration of fish and plant culture where fish culture increases nutrient concentrations of irrigation water and plant culture uses those additional nutrients to produce food or ornamental plant crops. Additional benefits include water quality improvement as effluent nutrient concentrations are reduced after passage through the aquaponics system.

The project had three components

- Working with 2 aquaculture producers to evaluate their site, design an aquaponic module consistent with their fish production system and quantify water quality improvements and initial aquaponic production.
- Conduct a workshop supplying information on how to design, construct and maintain an aquaponic system drawing on our experience with cool temperature flowing water aquaponic systems.
- Evaluate potential plant cultivars to be used in a cool temperature flowing water aquaponic system.

Aquaponics has been promoted for use with recirculating fish culture. A wide variety of crops have been grown in these systems including warm season crops like tomatoes, basil, chives and cucumbers. Leafy greens such as lettuce and Chinese cabbage have also been grown. Fish production often covers operating expenses while plant culture yields most of the profits. Aquaponics has not been generally applied to lower tech, small scale flow-through systems possibly due to the wider diversity of water quality in these systems. Source water quality (temperature regime, major ion, and nutrient concentrations) is highly variable from site to site unlike recirculating systems where the impact of source water quality is diminished by the influence of fish culture. The high diversity of flow-through systems makes it difficult to generalize between systems and has been an obstacle to implementation of the technology.

Our research at the West Virginia University Aquaculture Center at Reymann Memorial Farm has demonstrated that aquaponics may be integrated into a flowing water fish production system. A diversity of crops (watercress, lettuce, kohlrabi, nasturtium, Swiss chard) had been grown in the system prior to the initiation of the project with nutrient removal of up to 25% of NH_3, 22% of the NO_3 and 7 % of PO_4.

In this project we partnered with two fish producers, Wilson Mill Farms who produce trout for the wholesale and retail food market and Rainbowhead Farms who produce a variety of fish generally sold to individuals to stock ponds. Both producers had some knowledge of aquaponics but had not attempted to incorporate aquaponics into their production module. Site visits were made to each farm to evaluate the site, conduct extensive interviews with the farmers as to what they wanted to achieve with an aquaponics operation. Water samples were also taken at several locations so that water quality could be evaluated.

2. Aquaponics Implementation

A. WVU Aquaculture Facility

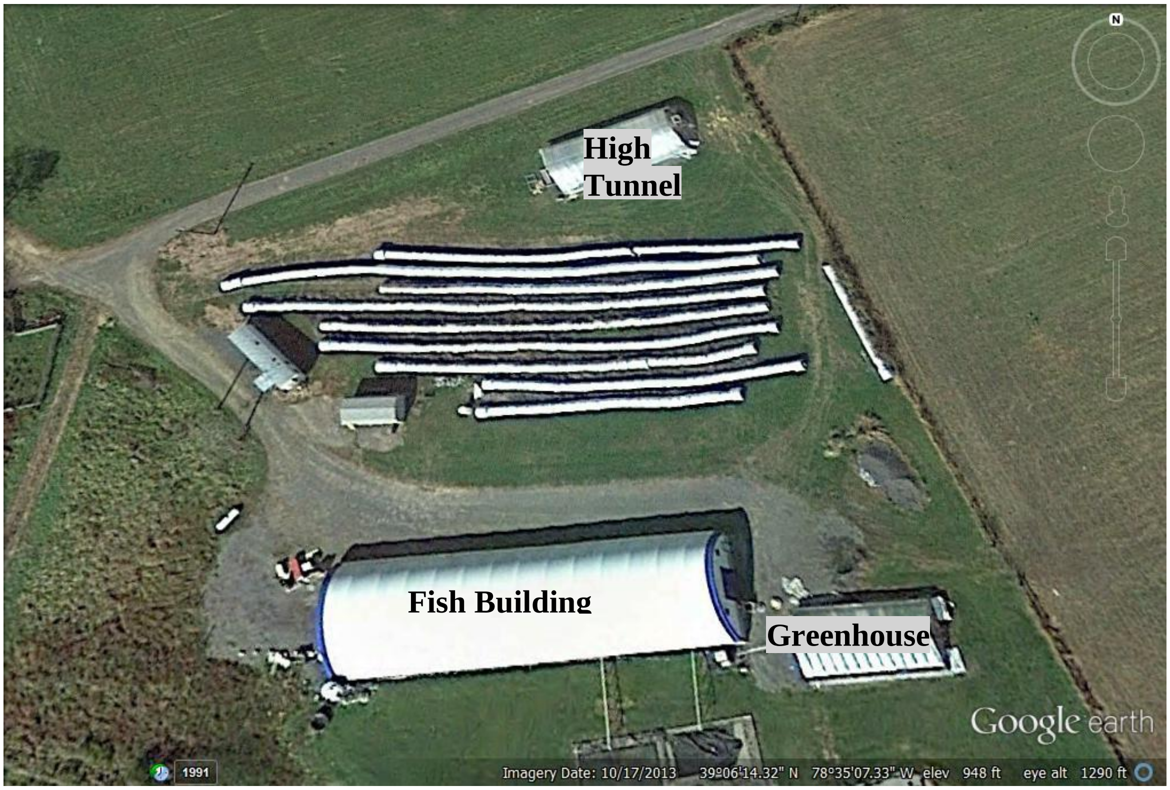


Figure 1. WVU Aquaculture Facility with the Fish Building and Aquaponics Greenhouse and High Tunnel labeled.

The WVU Aquaculture Facility consists of a Fish Building which contains linear raceways and circular tanks where trout are cultured, an aquaponics greenhouse where replicated experiments are conducted and the aquaponics high tunnel which is operated as a production facility. The water source for the facility is a natural spring that supplies about 350 gpm. Water flows through four levels through 8 individual production units before it is discharged. A portion of the effluent is pumped to both the aquaponics greenhouse and high tunnel.

Both the high tunnel and the greenhouse are 26’ x 48’structures with aquaponic channels and are oriented with the long axis E-W. The greenhouse channels are constructed of plywood with an EPDM liner. Each channel is 15” wide and 8’ long and oriented perpendicular to the greenhouse. There are 33 channels allowing for adequate replication within experiments. Effluent from the linear raceways is pumped into a manifold in the greenhouse which distributes the effluent to each channel. Influent velocity to each channel is controlled independently via a ball valve. Height of the effluent (generally 6-9”) within the channel is controlled by a standpipe.

There are four large channels (4’7” wide x 45’ long) constructed of dry stacked concrete block on a fine gravel base and covered with a white Dura-skrim® R20WW (Raven Industries) liner The block was stacked such that the channel was 30.5 cm deep. The trout effluent was pumped to the high tunnel and distributed via a PVC manifold. Flow into each channel was controlled via a ball valve. Water depth was maintained at 9" with a standpipe drain.

B. Wilson Mill Farms

Figure 2. Aerial photo of Wilson Mill Farms with the raceway levels labeled (B-F) and the proposed location of the aquaponics high tunnel.

Fish Production System

Wilson Mill Farms (WMF) is a trout farm with a spring water source that provides in excess of 800 gallons/min of high quality water with cool temperatures year-round. The spring water is captured via a retention pond and an aqueduct that feeds the raceway system. The raceway system consists of 6 levels running in series so that level A flows into level B etc. Each level consists of 8-10 raceways running parallel to each other. Quiescent zones are present at the end of each raceway providing solids capture. Since water flows from one raceway level to the next, nutrient and solids concentrations are expected to be highest at the end of the raceway system.

High Tunnel

During the site visit several locations were evaluated as potential sites to place the aquaponics system. The preferred site was north of Level E, alongside Level F as indicated in Figure 1.

This site was preferred because it was flat, was relatively unshaded, and was close to the raceway system, minimizing plumbing runs. Raceway effluent can be taken from either Level E or Level F depending on which is easiest. The site will accommodate a 26' x 48' high tunnel which has proven to be large enough to initiate an aquaponics system without being so large as to be overwhelming. A substantial quantity of produce can be grown within this structure. It is expected that the high tunnel will be oriented parallel to Level F which is basically along the North-South axis. At this latitude high tunnels can be oriented either N-S or E-W.

C. Rainbowhead Farm

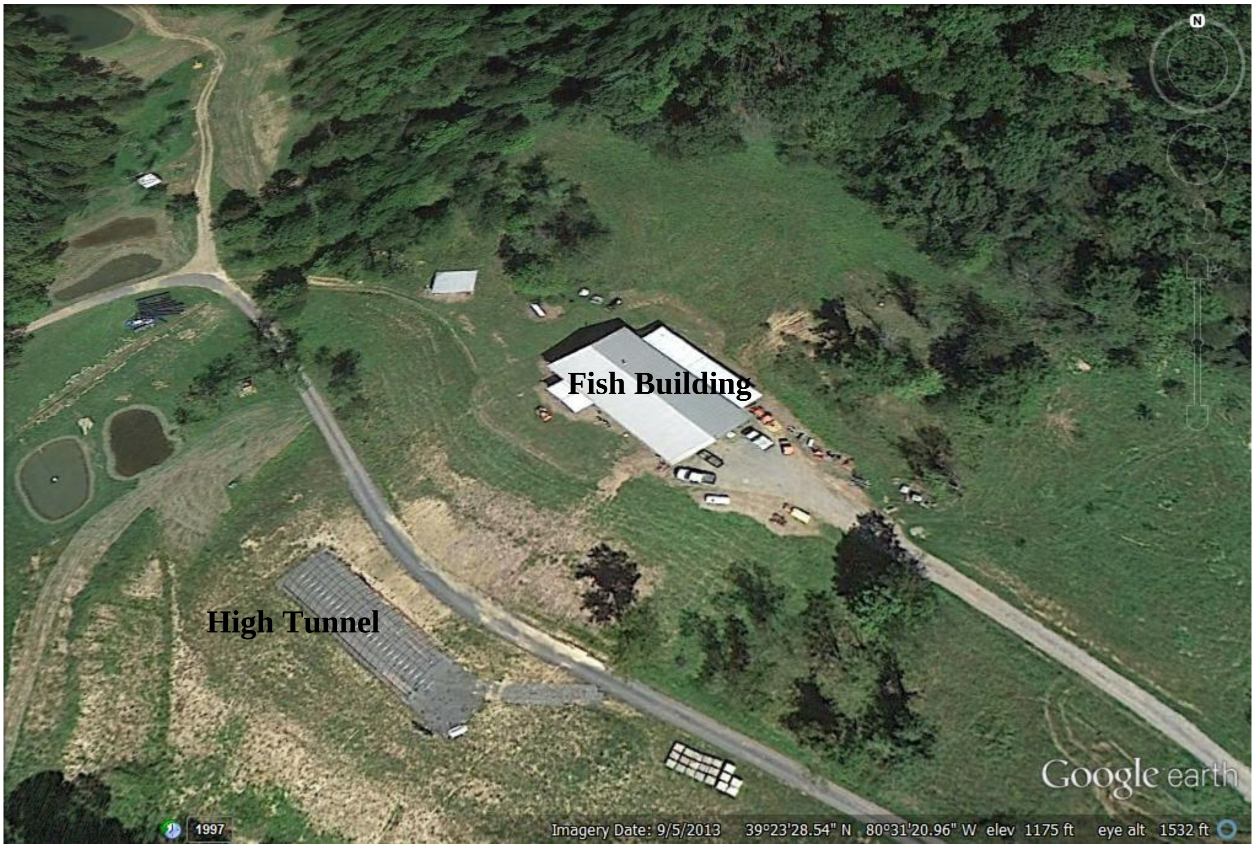


Figure 3. Aerial photo of Rainbowhead Farms with the location of the Fish Building and high Tunnel indicated.

Fish Production System

Rainbowhead Farms (RHF) sells a wide variety of live fish including trout, perch, largemouth bass, and blue gill. Fish are held in 400 – 600 gallon tanks in an enclosed building or in outdoor ponds. It is expected that only the tanks in the building will be incorporated into an aquaponic system. Water supply dictates both the quantity and type of fish present on the farm. Water is supplied by a well and is limited to ~1,600 gallons per day. The well water is stored in a large tank within the building to allow the well water temperature to equilibrate with ambient fish tank temperatures. In this system, water temperature will vary seasonally allowing the culture of cool water fish such as trout and perch in the winter and warm water fish such as bass and blue gill in the summer. The fish tanks are equipped with filters which remove solids and provide a medium for nitrification.

High Tunnel

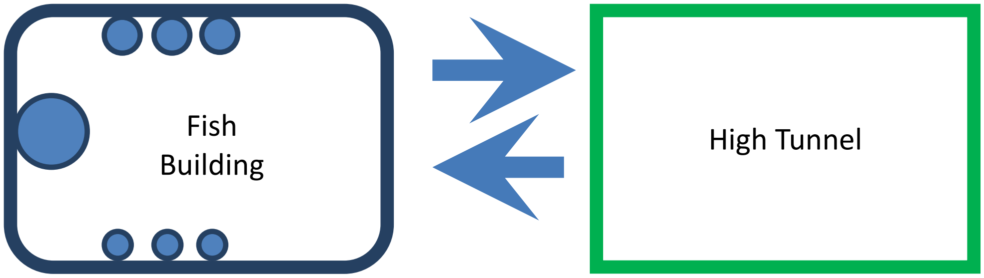
After discussions with the farmer it was decided that the high tunnel enclosing the aquaponics system should be placed down the hill and across a gravel road from the fish building. The location of the fish building and the partially constructed high tunnel are labeled in the photo above. This location, reasonably close to the fish building, minimized plumbing runs and was adjacent to an existing gravel road which would allow the easy movement of supplies to the high tunnel and crops to be loaded onto trucks for delivery.

We recommended that a 26’ x 48’ high tunnel be constructed on the site as this is sufficiently large to produce a large volume of crops but not so large as to be overwhelming. Additionally, high tunnels can be easily expanded through the insertion of additional sections. However, the farmer decided that he wanted to start with a larger high tunnel and a 30’ x 90’ high tunnel kit was purchased.

Aquaponics System

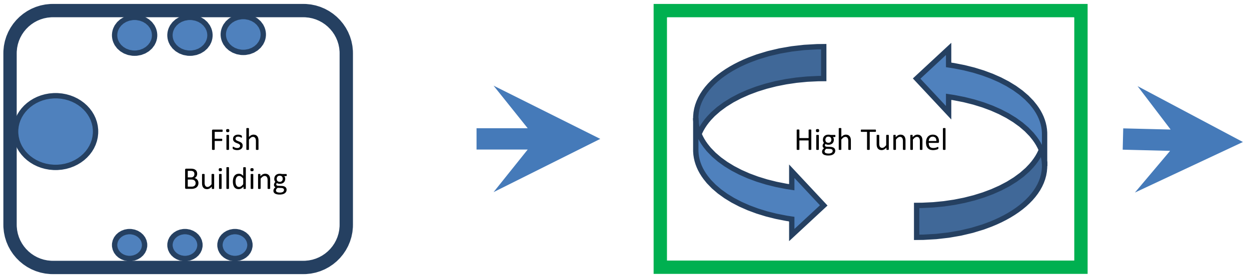
Two aquaponics systems, listed below, were proposed. The farmer chose alternative B.

Alternative A: Integrate the aquaponics system into the fish production system so that water flows from the fish tanks into the aquaponics system and then returns to the tanks. This would require the aquaponics system to be close to the fish building, probably in the parking lot. The system will be more complex than a flow-through system, but has the potential to reduce water usage and filtration costs in the current fish production operation. It is also very similar to traditional aquaponics systems. Temperature control may be an issue as passage through an unheated greenhouse at night in winter will cool the water. This may require installation of a heating system for the high tunnel or a heater for the water returning to the fish building. In summer, high water temperatures may be an issue if the high tunnel is not well vented and air temperatures are high.



Alternative A

Alternative B: Place the high tunnel in the meadow across the road. Effluent from back flushing the filters would supply the aquaponics system. This effluent has a total suspended solids content of 139 mg/L (see Table 1) and particles averaged 1.125 µm. The solids will need to be removed before release into the aquaponics system. The easiest way to do this is to pump the effluent into a large tank with a bottom drain. The solids can then settle and the liquid portion of the effluent can then be released into the aquaponics system. A pump would circulate the effluent within the aquaponics channels preventing oxygen depletion.



Alternative B

There is a limited volume of water available for the aquaponics system which will have consequences on all parts of the system. Nutrient concentrations will be highest when fresh effluent is released to the aquaponics component. This will decrease as the plants remove nutrients to support growth. Secondly, if there is no outside source of heat other than the solar heating of the high tunnel, water temperatures may become quite cold during winter months. Effluent will enter the high tunnel at ambient temperatures within the fish building but as the volume is limited, the heat embodied in the effluent cannot maintain temperatures within the high tunnel. Due to low temperatures and limited light during the winter, it was suggested that the farmer shut the aquaponic system down between mid-December and early February.

D. Plant Growing Systems

Similar aquaponics systems were recommended for both farms. Common growing systems used in aquaponics are channels with floating rafts, gravel beds operated either as continuous flow or ebb and flow, and the nutrient film technique (NFT). Solids in the raceway effluent have the potential to clog NFT tubes as well as foul gravel beds. Initially, the easiest and most trouble–free system is channels with floating rafts and it is expected that this is the system that will be implemented. The floating raft system is the same as is used at RMF. If possible channels should be oriented parallel to the N-S axis of the high tunnel thereby reducing shading effects due to channel walls.

Channel dimensions will need to reflect anticipated tray dimensions as well as plant culturing practices. Width of the channels should be no greater than is comfortable to reach across. Length of the channels will reflect whether batch or continuous culture is anticipated. If batch culture, where the entire channel is sown and subsequently harvested at once, is chosen then shorter channels may be preferable. Continuous culture will support either short or long channels depending on the crops chosen. In continuous culture or culture of crops with a long harvest season, opportunities to clean any accumulated solids from the channel may be limited.

E. Water Quality

Grab samples were taken from source water to the fish production tanks or raceways and effluent prior to entering the aquaponics system at the WVU Aquaculture facility, Wilson Mill Farms and Rainbowhead Farms to determine source water quality and whether the effluent was likely to support aquaponic production. The source water for both WVU AF and WMF was a spring while RHF source water came from a well. Water temperature at all sites was fairly similar and was relatively stable as it flowed through the fish production system. It is expected that the temperature of the source water for RHF will vary seasonally as it is stored in a large tank so that the pump can keep up with demand. Source water pH was circum-neutral and similar at all sites as well. Specific conductance, an indicator of total dissolved solids was lowest at the WVU AF, higher at WMF and highest at RHF but in no instance was the specific conductance too high to support aquaponic crop production. In fact, it may indicate more available micronutrients. The concentrations of the metals that were analyzed (aluminum, calcium, iron, magnesium and manganese) except calcium were all low. Calcium concentrations were highest at WMF and similar at WVU AF and RHF. There was little difference in any of these parameters between the source water and the effluent produced through fish production.

Table 1. Water quality parameters at Reymann Memorial Farm, Wilson Mill Farms and Rainbowhead Farms. Data corresponding to the source water and the effluent from the fish rearing tanks is presented. Not all parameters were collected at each site.

	WVU Aquaculture Facility		**Wilson Mill Farms**		**Rainbowhead Farms**	
Parameter	**Source**	**Effluent**	**Source**	**Effluent**	**Source**	**Effluent**
pH	6.82	6.90	7.14	7.45	7.48	7.50
Temperature (°C)	12.5	12.4	11.6	12.1	13.4	13.4
Specific Conductance (µS/cm)	161	162	268	259	338	338
Total Suspended Solids (mg/L)	0.60	4.15	0.00	1.20	1.00	139
Mean Particle Size (µm)		2.06		0.64	0.80	1.125
Alkalinity as mg/L Ca CO_3	78.6	79.1	140.3	142.9	189	166
Ammonium (mg/L)	0.02	0.26	0.0	0.28	0.19	0.13
Nitrite (µg/L)	1.1	1.9	0.7	14.7	0.88	83.4
Nitrate (mg/L)	0.25	0.28	0.89	0.62	0.00	1.91
Phosphate (mg/L)	0.11	0.14	0.02	0.06	0.05	0.11
Sulfate (mg/L)					2.0	6.9
Aluminum (mg/L)	<0.01	<0.01	0.09	0.12	0.09	0.79
Calcium (mg/L)	23.4	24.1	146.0	152.0	37.6	33.5
Iron (mg/L)	0.05	0.05	0.06	0.16	0.28	0.86
Magnesium (mg/L)	2.66	2.69	5.91	6.07	4.96	4.7
Manganese (mg/L)	<0.01	<0.01	0.01	0.03	0.21	0.11

Total suspended solids and nutrient concentrations however, did change and the difference between source and effluent reflected differences in where the effluent was obtained. Suspended solids concentrations at WVU AF and WMF increased in the effluent with a greater increase at WVU AF reflecting the higher fish densities at the time the samples were taken. The magnitude of these increases was minimal when compared with the increase between source and effluent at RHF which went from 1 mg/L in the source to 139 mg/L in the effluent. The source of the effluent however was filter backwash and would be expected to be high in suspended solids. This represents a concern regarding the operation of an aquaponics component in that if the solids are not removed prior to entering the aquaponic channels they will decompose releasing nutrients and reducing the effectiveness of nutrient removal. As well, oxygen concentrations within the root zone of the plants will be reduced which may retard growth or if extreme cause plant mortality.

Ammonium concentrations were 0.19 mg/L in the RHF source water and decreased slightly in the effluent while concentrations increased around 0.2 mg/L between source and effluent at WVU AF and WMF. Source water nitrate concentrations were below detection for RHF but effluent concentrations were more than double the concentrations at the other sites. This would be expected as the system is a hybrid between a flow-through and a recirculating system so the tank water has a lot of contact with both the filter and surfaces that have been colonized with nitrifying bacteria. A WMF nitrate concentrations decreased between source and effluent possibly due to uptake by algae growing on raceway surfaces. Source water phosphate concentrations were highest at WVU AF and in all cases increased slightly between source and effluent.

Due to constraints on water availability, the aquaponic system at RHF will be operated in batch mode with complete replacement of effluent daily. The plants growing in the system will be exposed to the highest nutrient concentrations when the effluent is replaced and those concentrations will decrease as the plants take up nutrients to support growth. This system had the potential to achieve the greatest nutrient removal but also has the potential to be nutrient limiting. A mass balance was done to determine how much nitrogen and phosphorous would be delivered to the aquaponic system based on an estimated 1,600 gallons/day of effluent.

Table 2. Mass balance of nitrogen and phosphate availability to aquaponic crops based on measured nutrient concentrations and an average influent velocity of 20 gal/min for the WVU AF and an estimated supply of 1,600 gal/day of effluent at Rainbowhead Farms.

	Nitrogen (mg/day)	Phosphate (mg/day)
WVU Aquaculture Facility	58,864	15,261
Rainbowhead Farms	12,839	666

This mass balance indicates that compared with the WVU AF, the aquaponic system at Rainbowhead Farms will receive substantially fewer nutrients and may need to either reduce the amount grown or supplement with an outside fertilizer source.

F. Outcomes

Both fish producers were excited about the potential to include aquaponics into their operation. However, the producer at Wilson Mill Farms withdrew from the project as he put his farm up for sale. The producer at Rainbowhead Farms experienced a slope failure that threatened his entire business and so was unable to complete construction of his aquaponic system. He has partially completed his high tunnel and intends to install his aquaponic system. The information supplied in this project gave both producers the confidence that their effluent was suitable for aquaponic production and they received a substantial amount of information regarding the construction and operation of an aquaponic system. Nevertheless, the implementation of an aquaponics system is not standard technology and that has proved to be a substantial barrier.

3. Aquaponics Workshops

Two all-day aquaponics workshops were held at the West Virginia University Aquaculture Center at the Reymann Memorial Farm on September 26 and October 17, 2013. Originally only one workshop was scheduled but an additional workshop was added due to high demand. The first workshop had 28 participants and the second had approximately 20 participants. Participants included extension agents, individuals who were interested in setting up an aquaponics system for home use as well as those who were interested in setting up an aquaponics business. The workshop consisted of several talks covering the basics of aquaculture and aquaponics and then a tour of the Aquaculture facility.

Speakers at the workshop included Dr. Kenneth Semmens, Aquaculture Specialist with WVU Extension, Dr. Nicole Waterland, assistant professor in Horticulture at WVU and Dr. Karen Buzby, postdoctoral fellow in Environmental Engineering at WVU. The program presented information on fish culture, plant culture and water quality. The fish culture portion of the program included the basics of flow-through raceway operation, potential fish species to culture and basic fish culture information. The plant culture segment focused on plant requirements for growth, the common plant growing techniques used in aquaponics, how to provide good growing conditions within an aquaponic system and a summary of plants we have successfully grown in an aquaponic system. The water quality segment described source water options for aquaculture, the degradation in water quality associated with fish culture and documented water quality improvements associated with aquaponics.

Workshop attendees were divided into three groups to tour the facility. One group went to the Fish Building which houses the flow-through raceways and contained rainbow trout being raised for consumption. A second group went to the Aquaponics Greenhouse which is designed to allow controlled experiments into aquaponic plant production. A third group went to the Aquaponics High Tunnel which is designed as a full scale aquaponic production facility. Since the groups were relatively small, there was ample opportunity for attendees to ask questions and examine all components of both the fish and plant culture operations.

4. Plant Screening Trial

A large scale plant screening trial was conducted to provide growers with information regarding stand establishment and production of aquaponic crops. Originally we intended to conduct screening trials in three separate aquaponic facilities, however one farmer dropped out of the project and the other encountered unexpected delays in the completion of his aquaponic high tunnel. Therefore, the trial conducted at the WVU Aquaculture Center was expanded to provide as much information as possible.

The screening trial had three treatments; low flow, high flow and amended high flow. The low flow treatment delivered effluent from the flow-through raceways at 5 gal/min while the high flow treatment delivered effluent at 20 gal/min. The amended treatment received 20 gal/min and the vermiculite growing medium was amended with 50% composted fish solids. As the only nutrient source for the aquaponic crops was the raceway effluent, the screening trial manipulated nutrient availability. The low flow treatment received the fewest nutrients while the amended high flow treatment received the most.

The screening trial was conducted in the Aquaponic High Tunnel. Three plant growing channels (4’7” wide x 45’ long) constructed of dry stacked concrete block on a fine gravel base and covered with a white Dura-skrim® R20WW (Raven Industries) liner were used. The block was stacked such that the channel was 30.5 cm deep. The trout effluent was pumped to the high tunnel and distributed via a PVC manifold. Flow into each channel was independently controlled via a ball valve. Water depth was maintained at 9” with a standpipe drain.
We evaluated 34 cultivars which can grouped into the following categories: lettuce (*Latuca sativa* ‘Rex’ and ‘Rhazes’), Asian greens (red rain (*Brassica juncea*), mizuna (*Brassica rapa var. japonica*), tatsoi (*Brassica rapa var. narinosa*), Tokyo bekana (*Brassica rapa var. chinensis*), vitamin green (*Brassica rapa var. narinosa*), and shungiku (*Glebionis coronaria*)), mustard greens (*Brassica rapa japonica group* Suehihung No. 2, *Brassica juncea* Southern Giant Curled and ‘Red Splendor), other greens (minutina (*Plantago coronopus*), cresses (*Lepidium sativum* ‘Persian Cress’and ‘Wrinkled Crinkled Cress’, arugula (*Eruca sativa* Arugula, and ‘Surrey’), wild arugula (*Diplotaxis tenuifolia* ‘Sylvetta’) and Italian dandelion (*Cichorium intybus* ‘Clio’), vegetables (kohlabi (*Brassica oleracea gongylodes group* ‘Winner’, Swiss chard (*Beta vulgaris* ‘Peppermint’, and beets (*Beta vulgaris* ‘Bull’s Blood and ‘Early Wonder Tall Top’) and herbs (sorrel (*Rumex acetosa*), green shiso (*Perilla frutesce*), cilantro (*Coriandrum sativum* ‘Santo’), Italian oregano (*Origanum x majoricum*), lovage (*Levisticum officinale*), chive (*Allium tuberosum* ‘Fine Leaf’), parsley (*Petroselinum crispum* ‘Darki’), garlic chive (*Allium tuberosum* ‘Nira’), salad burnet (*Sanguisorba minor*), winter savory (*Satureja montana*), sage (*Salvia officinalis* ‘Extrakta’) and rosemary (*Rosemarinus officinalis*)). All seeds were purchased from Johnny’s Selected Seeds, Winslow, ME.

Plants were grown in styrofoam Speedling® trays to which vermiculite or the fish solid/ vermiculite mixture was added as a growing medium. Seeds were sown directly into the Speedling® trays. Most cultivars were sown into 128 cell trays. However, crops that were thought to be more marketable at a larger size or matured to a larger size (head lettuce, kohlrabi, cilantro, Swiss chard, beets) were sown into a 32 cell tray. The 128 cell trays were sown using a vacuum seeder while the 32 cell trays were sown by hand. The Speedling® trays were placed 4 trays across each channel such that each row contained one cultivar as depicted below. Cultivars were placed in the same order and at the same distance from the influent across all channels. Cultivars sown into 32 cell trays were placed at the top of the channel nearest the influent when sown.

The tested cultivars were broken into 2 sets due to space constraints. All cultivars in set 1 were sown on 7/18/2013. As space became available, due to harvest of cultivars in set 1, cultivars in set 2 were sown. Sowing dates for cultivars in set 2 ranged over 45 days (8/26/2013 to 10/10/2013). In all cases, an individual cultivar was sown across all treatments on the same date. Additionally, where there were groups of cultivar types, such as mustard greens, the cultivars within a type were sown on the same date to facilitate comparison. Exceptions include the herbs which were sown in both sets and 2 different lettuce cultivars that were sown one to each set. Newly sown 128 cell trays were placed directly downstream of any 32 cell trays present in the channel such that the most recently sown trays were closest to the top of the channel and cultivars that had been in the system the longest were furthest from the influent.

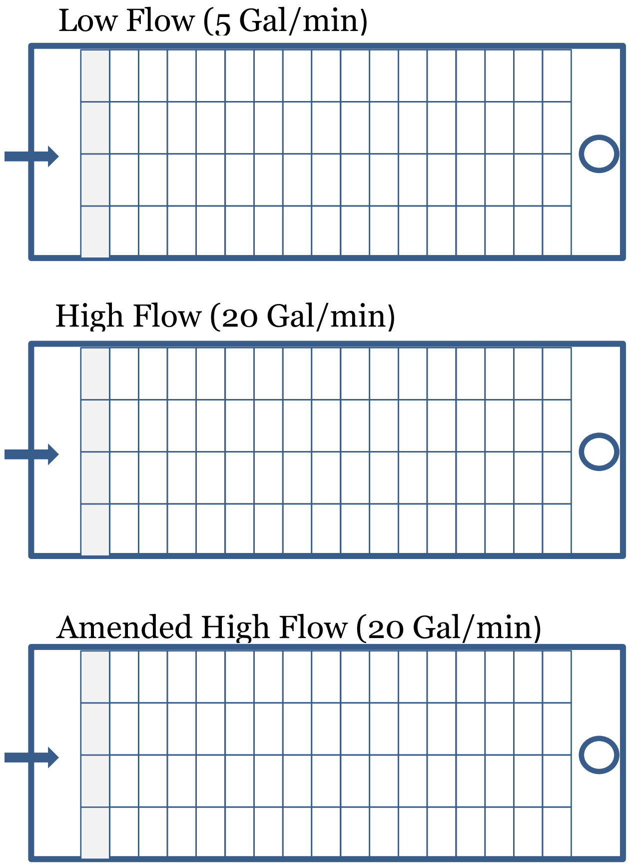


Figure 4. Schematic of the screening trial layout. The three channels are depicted; one received low flow of aquaculture effluent, one received high flow and the third received high flow and the growing medium was amended with fish solids. Each channel contains 17 rows of Speedling trays. Each row consists of 4 trays and is planted in a single cultivar. The rows of trays were arranged so that each cultivar was in the same position within the channel (depicted by the shaded row). There is a standpipe drain at the end of each channel.

We evaluated each cultivar using three metrics; stand establishment, harvest biomass and individual biomass. Stand establishment (number of filled cells) was assessed on each tray two to four weeks after sowing. Cells were thinned to two plants per cell if necessary. Each cultivar was harvested when it reached harvestable size based on horticultural information and product size in grocery stores. Most cultivars were harvested using an electric fillet knife that cut the plant stems cleanly approximately 1 cm above the surface of the tray. In cultivars where the stem was too tough for the fillet knife to cut cleanly (e.g. shiso), scissors or a regular knife was used. Each tray was harvested separately and a fresh weight determined. Individual biomass at the time of harvest was calculated by dividing harvest biomass by the number of filled cells. Changes in water quality between the beginning and end of the channel were quantified every two weeks by taking water samples at the influent and at the end of each channel. Samples were immediately placed on ice until they were transported back to the lab where they were held at 4°C. The samples were analyzed according to methods delineated by APHA (1995) for total suspended solids (TSS) (2540 D), ammonium (4500-NH_3 phenate method), nitrite (4500-NO_2^- colorimetric method), nitrate (4110-NO_3^- ion chromatography with direct conductivity detection) and phosphate (4500-P ascorbic acid method).

A. Stand Establishment

Overall, stand establishment was high with an average across all cultivars and treatments of 74% (Table 3). Nevertheless, two cultivars, garlic chive and sage, had such poor stand establishment that they were removed from the trial. Growth of these cultivars would need to be evaluated with transplanted seedlings which was outside the scope of this trial. Treatment effects on stand establishment were generally minor. However, there was a group of cultivars including the Asian greens vitamin green and shungiku, both beet cultivars, and the herbs parsley and salad burnet that had significantly higher stand establishment on the amended treatment. Seed germination and subsequent stand establishment will be greater if environmental conditions including water, oxygen availability and temperature approach optimum conditions. As we did not measure these parameters, it is unclear which, if any, may be affecting stand establishment.

Conversely, a few cultivars, including the bibb lettuce 'Rex' and the Italian dandelion 'Clio' had lower stand establishment on the amended treatment. The bibb lettuce 'Rex' was the only pelleted seed used in the experiment. Pelleted seed is coated with a mineral coating that may hinder germination under very moist conditions as the coating may retain water close to the seed reducing oxygen availability (Johnny's Selected Seeds, 2014). We observed that the amended treatment appeared to be wetter than the vermiculite used in the other treatments. The interaction between the two may have reduced germination. The other lettuce cultivar 'Rhazes' was not a pelleted seed and did not have reduced stand establishment on the amended treatment.

There are advantages and disadvantages to sowing seeds directly into the trays where the crops will be grown. Sowing directly allows the grower to avoid the labor involved in transplanting seedlings and avoids mortalities or reduced growth due to transplant shock. Additionally, there is no requirement for a temperature and humidity controlled area to establish seedlings. Nevertheless, conditions within the channel must meet the seeds germination and establishment requirements. Furthermore, it is unlikely that all seeds will germinate leading to unfilled cells within the trays. This can be compensated for by resowing seeds into unfilled cells. In addition, some thinning of excess plants will likely be required.

Table 3. Stand establishment (mean ± standard error, n=4) for each cultivar. Stand establishment was defined as the % filled cells in a tray. ANOVA p values are given, with homogeneous groups indicated by the same superscripted letter.

	Stand Establishment (% Filled Cells)			
Cultivar	**Low Flow**	**High Flow**	**Amended**	**P value**
LETTUCE				
'Rex'	93.8 ± 7.2	91.4 ± 3.5	75.8 ± 8.2	0.059
'Rhazes'	80.5 ± 8.8	96.1 ± 3.0	94.5 ± 5.3	0.319
ASIAN GREENS				
Red Rain	90.0 ± 2.3^{a}	93.4 ± 1.6^{ab}	96.3 ± 0.7^{b}	0.027
Mizuna	85.2 ± 5.8^{a}	92.6 ± 1.4^{ab}	96.1 ± 3.2^{b}	0.023
Tokyo Bekana	81.3 ± 6.1^{a}	82.4 ± 1.5^{b}	93.4 ± 6.0^{b}	0.000
Vitamin Green	78.1 ± 6.1^{a}	83.2 ± 3.4^{a}	93.8 ± 4.5^{b}	0.009
Shungiku	67.4 ± 2.2	66.4 ± 5.9	66.0 ± 9.3	0.985
Tatsoi	90.8 ± 5.0	88.1 ± 2.9	90.8 ± 4.9	0.727
MUSTARD GREENS				
Suehlihung No. 2	93.0 ± 4.5	89.5 ± 1.0	95.9 ± 1.7	0.059
Southern Giant Curled	94.5 ± 1.9^{ab}	90.0 ± 1.9^{a}	97.3 ± 1.6^{b}	0.011
Red Splendor	93.2 ± 2.0	94.5 ± 1.6	93.6 ± 1.7	0.614
OTHER GREENS				
Minutina	98.8 ± 1.0	96.7 ± 1.5	99.6 ± 0.5	0.075
Italian Dandelion	51.6 ± 13.2	47.9 ± 8.9	29.7 ± 11.5	0.139
Arugula	86.5 ± 2.1^{a}	88.5 ± 0.5^{a}	94.1 ± 2.7^{b}	0.003
Arugula ‘Surrey’	88.1 ± 3.8	83.6 ± 2.0	87.5 ± 7.7	0.447
Arugula ‘Sylvetta’	82.0 ± 8.2	84.2 ± 2.0	87.5 ± 5.2	0.450
Persian Cress	97.1 ± 2.1	97.5 ± 0.5	95.9 ± 1.7	0.518
Wrinkled Crinkled Cress	95.5 ± 2.1	94.5 ± 1.1	96.1 ± 2.3	0.592
VEGETABLES				
Kolrabi 'Winner'	67.2 ± 11.6	84.4 ± 2.2	77.3 ± 17.0	0.335
Swiss Chard 'Peppermint'	38.3 ± 13.1^{ab}	21.1 ± 6.0^{a}	50.0 ± 3.6^{b}	0.012
Beet ‘Early Wonder Tall Top’	28.9 ± 13.6^{a}	28.1 ± 2.2^{a}	52.3 ± 11.5^{b}	0.015
Beet ‘Bulls Blood’	33.6 ± 5.9^{a}	28.1 ± 2.2^{a}	66.4 ± 16.2^{b}	0.002
HERBS				
Sorrel	90.4 ± 2.7	92.2 ± 2.2	92.4 ± 3.9	0.707
Green Shiso	76.8 ± 5.0	70.5 ± 3.6	68.2 ± 14.3	0.449
Cilantro	86.7 ± 10.6	91.4 ± 2.0	87.5 ± 9.2	0.795
Oregano	93.8 ± 2.8	91.4 ± 6.3	90.0 ± 1.7	0.447
Lovage	40.2 ± 3.4	39.1 ± 9.9	26.2 ± 12.4	0.146
Chive	86.9 ±5.4^{ab}	82.8 ± 3.1^{a}	93.9 ± 2.3^{b}	0.022
Garlic Chive ‘Nira’	22.9 ± 8.2^{a}	15.0 ± 2.9^{a}	43.6 ± 13.1^{b}	0.006
Parsley	68.4 ± 1.7	67.0 ± 5.3	80.5 ± 6.5	0.013
Sage 'Extrakta'	3.3 ± 1.1^{a}	3.5 ± 2.1^{a}	45.9 ± 10.5^{b}	0.000
Salad Burnet	32.4 ± 3.4^{a}	28.1 ± 5.9^{b}	90.6 ± 2.6^{c}	0.000
Winter Savory	77.5 ±5.1	79.1 ± 12.3	83.4 ± 2.2	0.747
Rosemary	69.5 ± 2.1	55.7 ±27.9	51.8 ± 7.4	0.928

B. Harvest Biomass

The cultivars evaluated varied widely in both time to harvest as well as harvest biomass (Table 1). Within set 1, the Asian greens grew the fastest and therefore were ready to harvest sooner than the other cultivars. The lettuce and other greens grew slightly slower but were still ready to harvest within 49 days. Kohlrabi was ready to harvest after 70 days. The herbs sorrel and green shiso also grew quickly and were ready to harvest after 42 – 49 days while the remainder of the herbs grew slowly with days to harvest exceeding 70 days. Many of the cultivars in set 2 also grew very quickly despite being sown in late summer to fall. The cresses were ready to harvest 36 days after sowing, the mustard greens were ready to harvest after 49 days and the arugula cultivars were harvested after 56 days. However, all of the herbs in set 2 grew slowly and were harvested 73 – 81 days after sowing as they had stopped growing.

Most cultivars grew well within this cool temperature, low nutrient aquaponic system. However, the vegetables Swiss chard ‘Peppermint’, and both beet cultivars grew poorly and achieved low biomass when they were harvested at the end of the experiment. These three cultivars were sown late in the experiment and did not grow well under the fall conditions. Previous studies have shown Swiss chard ‘Bright Lights’ does grow well in this system. It is unclear whether the poor growth was due to environmental conditions and performance might have been better earlier in the year or whether the cultivars were not suited to the system. The herbs oregano and rosemary and the arugula cultivar ‘Sylvetta’ also grew very poorly in all three treatments. It is unlikely that environmental conditions limited growth in these three cultivars as they were sown in late August and it must be concluded that these cultivars were not suited to cultivation within this aquaponic system.

On the other hand, many cultivars grew well. Kohlrabi produced the greatest biomass of any cultivar tested although it required 70 days to produce a crop. The bibb lettuce ‘Rex’ was also very productive and required only 49 days to produce a crop. Although most cultivars grew well, many took longer than the predicted number of days to reach harvestable size. For example, parsley was predicted to take 75 days to harvest but instead it took 112, Persian cress was predicted to take 21 days but instead it took 36 days. On the other hand, the Asian greens reached harvestable size slightly earlier than predicted.

Within each crop group, there were cultivars that outperformed the others in the group. Within the Asian greens this was Tokyo bekana, in the mustard greens this was Suehlihung No. 2, within the other greens minutina was most productive, kohlrabi was the most productive vegetable and cilantro was the most productive herb. It should be recognized that the bibb lettuce ‘Rex’, kohlrabi and cilantro were at the top of the channel closest to the influent and as such were exposed to the highest nutrient concentrations. These cultivars may not have attained the same biomass if they were placed further from the influent nutrient source. The cultivars assessed in this study had variable responses to the different treatments. Cilantro, salad burnet, parsley, oregano, minutina, and Swiss chard did not exhibit treatment differences in harvest or individual biomass. For all other cultivars, biomass attained in the low flow treatment was the lowest across all treatments.

Eight cultivars, including the better performing kohlrabi and bibb lettuce ‘Rex’, attained the greatest biomass under the high flow conditions. This group included cultivars grown at the top, middle and bottom of the channel. As such, nutrient limitation does not appear to be a factor for these cultivars and incorporation of fish solids into the growing medium negatively impacted growth. The growing medium in the amended treatment appeared much wetter than the standard vermiculite which may have impacted oxygen availability to the roots within the growing medium.

The remaining 18 cultivars, including all of the mustard greens, and most of the Asian greens, other greens and herbs, grew better in the amended treatment. For some cultivars, this was due to higher nutrient availability as both harvest biomass and individual biomass were greater when grown on fish solid amended vermiculite. However, for many cultivars increased production was due to an increase in stand development which offset decreases in individual biomass. The most dramatic of these was salad burnet where stand development increased from an average of 30% for the low and high flow treatments to 90% in the amended treatment. This resulted in a 10% increase in harvest production despite a 50% reduction in individual biomass as compared to the high flow treatment. In other cultivars, such as the Italian dandelion, stand establishment was poor under the amended treatment but individual biomass was considerably greater than in the other treatments leading to significantly greater harvest biomass. Understanding how both stand establishment and individual biomass interact is critical to maximizing both.

While production on the amended treatment was greater for many cultivars, frequently the increase in harvest biomass over the high flow treatment was minor. There may have been negative effects due to the high level of fish solids used that offset the growth increase due to increased nutrient availability. A cost/benefit analysis is required to assess whether the increased effort required to incorporate the fish solids translates into a sufficient increase in harvest biomass to be cost effective. Additional research is necessary into determining the optimum incorporation level for various crops.

Table 4. Harvest biomass (mean ± standard error, n=4) for each cultivar in each treatment are presented. ANOVA p values are given, with homogeneous groups indicated by the same superscripted letter. Sowing date and predicted and actual days to harvest are also reported. Plant type (annual (A), perennial (P) or biennial (B) is denoted for the herbs.

	Sowing	Days to Harvest		Harvest Biomass (g)			
Cultivar	**Date**	**Predicted**	**Actual**	**Low Flow**	**High Flow**	**Amended**	**P value**
LETTUCE							
'Rex'	7/18	50	49	655.0 ± 110.8^{a}	1343.8 ± 69.1^{b}	869.9 ± 212.6^{ab}	0.022
'Rhazes'	9/19	42	57	189.7 ± 8.1^{a}	161.4 ± 14.6^{a}	523.3 ± 17.2^{b}	0.018
ASIAN GREENS							
Red Rain	7/18	40	35	101.0 ± 7.0^{a}	519.8 ± 17.5^{b}	423.7 ± 42.4^{c}	<0.001
Mizuna	7/18	40	35	76.2 ± 9.1^{a}	620.5 ± 42.4^{b}	427.9 ± 46.1^{c}	<0.001
Tokyo Bekana	7/18	45	35	138.1 ± 18.2^{a}	927.5 ± 24.9^{b}	1106.4 ± 102.7^{b}	<0.001
Vitamin Green	7/18	40	35	143.9 ± 16.3^{a}	636.1 ± 49.2^{b}	894.3 ± 53.9^{c}	<0.001
Shungiku	7/18	45	42	71.1 ± 8.0^{a}	421.0 ± 51.3^{b}	626.3 ± 84.0^{c}	<0.001
Tatsoi	7/18	45	42	203.5 ± 29.9^{a}	807.7 ± 73.0^{b}	977.3 ± 157.8^{b}	0.001
MUSTARD GREENS							
Suehlihung No. 2	9/5	45	49	569.3 ± 25.2^{a}	1160.7 ± 138.4^{b}	1694.7 ± 108.1^{c}	<0.001
Southern Giant Curled	9/5	50	49	396.6 ± 21.0^{a}	998.1 ± 93.4^{b}	1649.0 ± 121.6^{c}	<0.001
Red Splendor	9/5	45	49	321.6 ± 25.7^{a}	920.8 ± 95.9^{b}	1157.0 ± 127.5^{b}	<0.001
OTHER GREENS							
Minutina	7/18	50	49	642.4 ± 51.3	1123.6 ± 111.8	857.4 ± 197.0	0.088
Italian Dandelion	8/26	48	73	29.5 ± 6.3^{a}	44.3 ± 9.4^{a}	471.5 ± 33.4^{b}	<0.001
Arugula	8/29	40	56	89.3 ± 9.0^{a}	869.6 ± 63.6^{b}	1095.4 ± 35.1^{c}	0.007
Arugula ‘Surrey’	8/29	40	56	81.9 ± 4.5^{a}	513.9 ± 35.0^{b}	568.6 ± 130.1^{b}	0.023
Arugula ‘Sylvetta’	8/29	50	56	26.1 ± 5.7^{a}	106.7 ± 13.6^{b}	58.0 ± 12.7^{a}	0.002
Persian Cress	10/10	21	36	186.0 ± 18.1^{a}	195.3 ± 16.3^{a}	257.8 ± 9.7^{b}	0.017
Wrinkled Crinkled Cress	10/10	30	36	93.3 ± 7.1^{a}	82.2 ± 2.5^{a}	138.0 ± 3.4^{b}	<0.001
VEGETABLES							
Kolrabi 'Winner'	7/18	45	70	1015.7 ± 68.8^{a}	2016.2 ± 151.5^{b}	1154.2 ± 202.8^{a}	0.002
Swiss Chard 'Peppermint'	9/30	55	46	12.8 ± 2.5	5.7 ± 2.0	11.6 ± 1.6	.079

Beet 'Early Wonder Tall Top'	9/30	45	46	15.3 ± 4.7^{a}	10.7 ± 2.2^{a}	52.6 ± 5.8^{b}	<0.001
Beet 'Bulls Blood'	9/30	58	46	6.2 ± 0.4^{a}	3.4 ± 0.4^{a}	29.5 ± 2.7^{b}	0.007
HERBS							
Sorrel (P)	7/18	60	42	334.7 ± 33.0^{a}	622.4 ± 58.9^{b}	504.7 ± 77.1^{ab}	0.022
Green Shiso (A)	7/18	80	49	143.5 ± 14.3^{a}	115.1 ± 24.0^{a}	217.6 ± 59.8^{b}	<0.001
Cilantro (A)	7/18	50	63	1012.4 ± 219.3	888.4 ± 78.2	781.5 ± 168.5	0.631
Oregano (P)	7/18	80	70	47.5 ± 8.7	93.6 ± 9.5	66.6 ± 27.3	0.225
Lovage (P)	7/18	90	74	496.2 ± 60.5^{a}	569.4 ± 45.1^{a}	207.2 ± 22.3^{b}	<0.001
Chive (P)	7/18	75	84	130.2 ± 19.0^{a}	138.9 ± 20.8^{a}	638.1 ± 140.7^{b}	0.024
Parsley (B)	7/18	75	112	116.8 ± 46.2	244.4 ± 99.3	370.5 ± 233.2	0.51
Salad Burnet (P)	8/26	70	73	600.9 ± 76.7	957.1 ± 179.2	1084.0 ± 115.1	0.068
Winter Savory (P)	8/26	100	81	32.1 ± 5.4^{a}	47.0 ± 8.7^{a}	120.5 ± 20.2^{b}	0.018
Rosemary (P)	8/26	80	81	3.4 ± 0.9^{a}	4.9 ± 0.7^{a}	13.2 ± 2.4^{b}	0.006

C. Water Quality

Soluble nutrient concentrations were low over the course of the experiment with average influent concentrations of 0.35 ± 0.03, 0.43 ± 0.08 and 0.19 ± 0.02 mg/L for ammonium, nitrate, and phosphate, respectively (Figure 5). Differences in effluent concentration were not significantly different among treatments for any of the nutrients ($p = 0.18, 0.72, 0.13$ for NH_4^+, NO_3^- and PO_4^{2-} respectively).

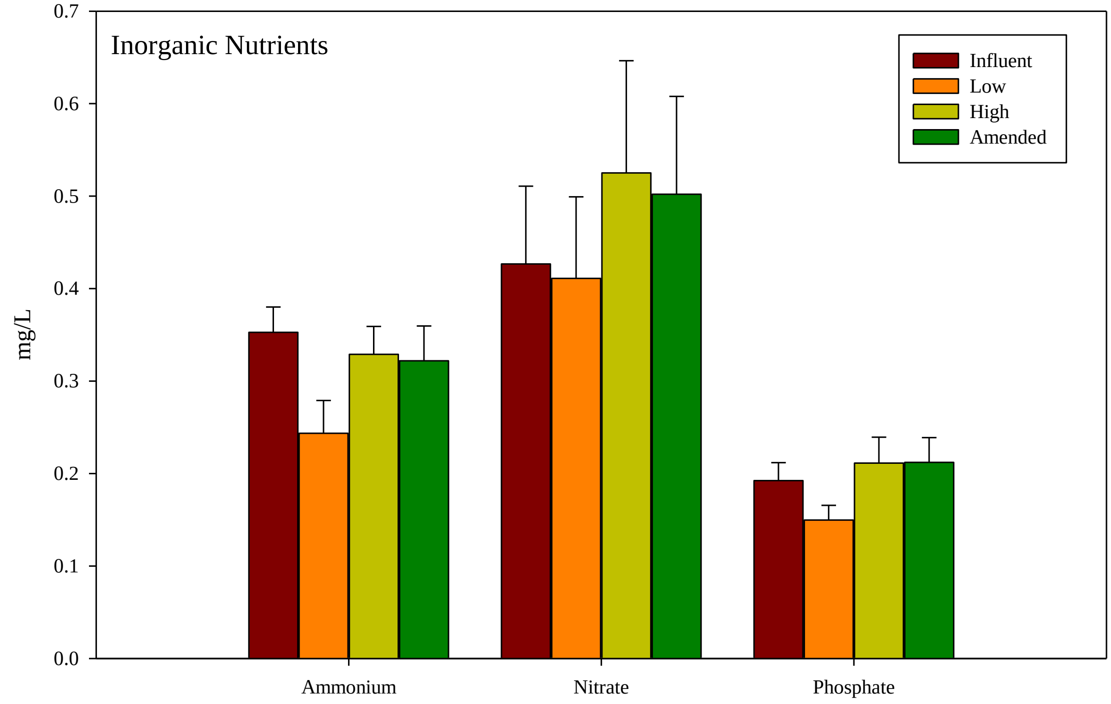


Figure 5. Inorganic nutrient (ammonium, nitrate and phosphate) concentrations (mean ± S.E>) at the channel influent and the outlets of each of the treatment channels.

Unlike the soluble nutrient concentrations, there were significant differences among treatments in the behavior of TSS (Figure 6). There were no significant differences in influent TSS concentration ($p = 0.76$). Effluent TSS concentration was significantly lower than the influent in the low flow channel ($p = 0.02$). In the high flow and amended treatments, effluent TSS concentration was lower than the influent, however differences were not significant ($p = 0.35$ and 0.16 respectively), perhaps due to high variability.

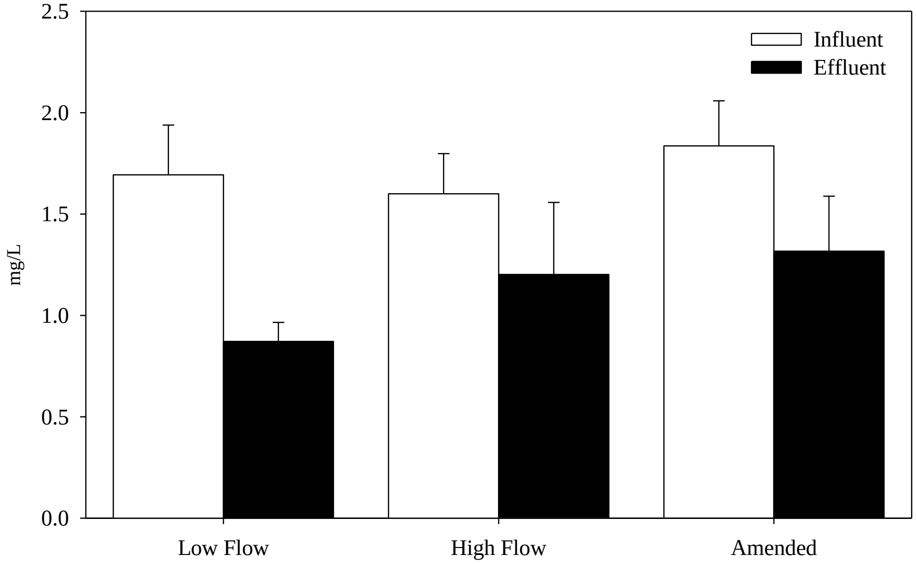


Figure 6. Total suspended solids concentrations at the influent and outlet of each channel.

D. Conclusion

The cultivars selected for this experiment comprise a variety of crop types. There were fast growers, such as the cresses and the Asian greens that matured quickly allowing rapid turnover of growing space but require more labor as they need to be harvested and resown. Another assemblage, consisting of the mustard greens, arugulas and lettuces did not grow as rapidly but have the potential to be harvested multiple times from one sowing. Multiple harvests from a single sowing can reduce both labor and material costs. Another major group were the herbs, which are a high value crop that can be harvested multiple times but tend to grow more slowly.

Within each group were cultivars that were more productive. For example, of the 3 arugulas, ‘Sylvetta’ did not grow well and while ‘Surrey’ grew better, Arugula was substantially more productive. Within the mustard greens, Suehlihung No. 2 produced more biomass than the other 2 cultivars. Persian cress was more productive than the wrinkled crinkled cress. These results demonstrate the importance of testing multiple cultivars, where available, to determine which cultivar grows best within a particular system’s constraints.

In addition, this experiment identified cultivars that were not suited to aquaponic production under these conditions. Examples include oregano and rosemary which grew very poorly under all treatments. Flow-through aquaponics has the potential to be more variable in terms of operating conditions because source water is not retained. To a large extent, source water is not modified by the passage through the fish rearing operation, other than an elevation of nutrient concentrations, and therefore the effluent reflects the temperature and chemical signature of the source water. The wide variety of source waters used in aquaculture including springs, well water, lake and stream water that could potentially be used in aquaponic culture, suggests that additional trials should be completed to give a more comprehensive understanding of how well these crops grow in aquaponic systems.

5. Project Summary

The objective of this project was to demonstrate the potential of aquaponics as a low-cost, low tech, sustainable part of a diversified, aquaculture production model. Taking the lessons learned in the design and operation of an aquaponics module at the WVU Aquaculture Facility, we evaluated the potential to implement aquaponics on two existing fish farms. At both it was determined that implementation was feasible. Location and design of an aquaponic system was provided to both producers. Unfortunately one producer withdrew from the project and put his farm up for sale. The second producer had a catastrophic slope failure that threatened his fish production building. Stabilizing the slope and repairing damage to the structure and in-ground plumbing slowed the construction of the aquaponics high tunnel. At this time the high tunnel is partially completed and the farmer is committed to finishing the project.

Two all day workshops were held at the WVU Aquaculture Facility. The workshops covered information regarding fish rearing, aquaponic system design, plant rearing and water quality. A tour of the facility including the fish rearing building, the research aquaponics greenhouse and the aquaponic production high tunnel allowed participants to examine a flow-through aquaponic operation and to ask questions in an informal setting.

A large plant screening trial where nutrient availability was manipulated provided aquaponics growers with stand establishment and crop production information on a wide variety of crops. The screening trial identified crops that were unsuitable for aquaponic production as well as ascertaining which cultivars were most productive.