[M.L. 2014] Project Abstract
For the Period Ending June 30, 2015

PROJECT TITLE: **Expansion of Greenhouse Production**
PROJECT MANAGER: Lana Fralich
AFFILIATION: City of Silver Bay, MN
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CITY/STATE/ZIP: Silver Bay, MN 55614
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2014, Chp. 226, Sec. 2, Subd. 06k

APPROPRIATION AMOUNT: $176.000

Overall Project Outcomes and Results

Minnesotans currently import over 90% of the food they consume each year. New developments in Controlled Environmental Agriculture (CEA) have the potential to allow year-round food production in cold climates like ours. These CEA approaches hold the promise of billions in new economic development along with increased environmental and human health producing environmentally sustainable and healthy food year-round in Minnesota. Victus Farms is a 9,000 ft2 controlled environmental agriculture facility (CEA) in Silver Bay, MN operated by researchers at the University of MN, Duluth. Victus Farms is aimed at developing/demonstrating an environmentally sustainable and economically viable approach to year-round food production in cold climates. It also conducts applied research to improve these CEA production methods, and education to communicate the benefits of CEA and train its future workforce.

LCCMR Funds were used at Victus Farms to explore the potential of a wide variety of crops and production methods. Specifically, we wanted to determine the revenues generated per square foot of greenhouse space for a variety of potential crops, and determine the best methods to grow these crops. We were able to determine that lettuce ($101.76/ft2), basil ($125.84/ft2) and hot peppers ($130.00/ft2) were the crops with the best economic potential. In addition, we concluded that given its large local market and ease of year-round growth, lettuce has the best overall potential. We were also able to determine the most consistent, environmentally sustainable and economically viable growth method was a hydroponic approach including both vertical thin films and deep water floating rafts. As the result of this project work and its dissemination, two new related businesses have been created in Northern Minnesota and several others are in the early stages of development. These CEA approaches have the potential to create a new multibillion-dollar sustainable food production industry in Minnesota.

Project Results Use and Dissemination

Since the LCCMR funded portion of our project began in June of 2014 we have conducted numerous dissemination activities. These include local, national and global presentations (13 total); Tours of the Victus Farms facility to a wide variety of groups/individuals (over 20 in total); Peer reviewed research publications (3); Technical Reports (10 total) and numerous media stories (8 total) in local newspapers, TV stations, Radio Stations and University of MN, communication outlets. Therefore, we have been fortunate to enjoy a great deal of interest in our work at Victus Farms over the past several years, and have had numerous opportunities to communicate our work to a broad audience from local hobbyists to community groups to private businesses to university researchers, to prominent, local, state and national policy makers. As the result of our project work and these widespread dissemination activities, two new CEA businesses (Mariner Farms and Wicked Fin Aquatic Farms) have begun operations in our region, and many others are in the early stages of development.

Environment and Natural Resources Trust Fund (ENRTF) M.L. 2014 Work Plan Final Report

Date of Report:	July 30th, 2016
Date of Next Status Update Report:	Final Report
Date of Work Plan Approval:	June 4, 2014
Project Completion Date:	June 30th, 2016

PROJECT TITLE: Expansion of Greenhouse Production

Project Manager:	Lana Fralich
Organization:	City of Silver Bay, MN
Mailing Address:	7 Davis Drive
City/State/Zip Code:	Silver Bay, MN 55614
Telephone Number:	(218) 226-4408
Email Address:	lanaf@silverbay.com
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Location: Lake County

Total ENRTF Project Budget:

ENRTF Appropriation:	**$176,000**
Amount Spent:	**$176,000**
Balance:	**$0**

Legal Citation: M.L. 2014, Chp. 226, Sec. 2, Subd. 06k

Appropriation Language:
$176,000 the second year is from the trust fund to the commissioner of natural resources for an agreement with the city of Silver Bay to expand and enhance a city-owned greenhouse facility to increase system production for locally grown food on a year-round basis and reduce water usage.

I. PROJECT TITLE: Expansion of Greenhouse Production

II. PROJECT STATEMENT:

Victus Farm's, located in the Silver Bay Eco-Industrial park, is a new partnership between the City of Silver Bay and UMD aimed at proving the economic viability of producing sustainable food and fuel year-round using a method that integrates fish, plants and algae in a closed loop system. The existing 8600+sq. ft facility is fully renewable, using biomass (wood pellets in flex fuel boilers) for heat, sunlight, recycled rainwater, and a future wind turbine or photovoltaics for electricity. The only other major input is organic fish feed. Outputs include fish, produce, rich compost and algal oil. Our goal is to demonstrate and improve the economic viability of this process to create a new sustainable industry for Minnesota and beyond. The facility also provides ongoing community education, systems research and future workforce training. Our production system has been evolving daily, and has already exceeded expectations. New innovative approaches have evolved that will lower costs and increase revenues. Increasing aquaponic food production could offset conventional agriculture production and eliminate many associated environmental problems such as nutrient pollution, sedimentation, soil erosion, herbicide and pesticide contamination. We plan to explore new ways to grow our fish and produce that will allow us to increase production per square foot, and reduce operational costs. We also plan to explore the addition of new plants and animals to diversify revenue sources and increase overall system revenues. Each project activity can be completed within Silver Bay's existing $1.5 million facility while providing continued research and education within the university system. The City is now developing the existing freshwater system into a commercial scale for private investment. If we can demonstrate the concept's economic potential, and a commitment to continued public research, the private sector will duplicate these systems across Minnesota.

III. PROJECT STATUS UPDATES:

Project Status as of: 12/31/14

In the first six months we introduced Tomatoes and Cucumbers. We tried three different growth methods for several tomato and two cucumber species. We report the total yields and sales resulting from each approach, and conclude with a recommendation for best species and growth method. We also designed and constructed vertical 'racks' for growing four different lettuce species, and compared each of their growth rates with those using a more conventional 'raft' approach. Achieving similar growth rates in vertical production systems would greatly enhance production per square foot, and reduce capital and operational costs. This vertical growth method would allow us to move our fish from the nine 2,000 gallon tanks to the greenhouse plant troughs. This eliminates the need for 2,000 square feet of building space, 18,000 gallons of water to heat and circulate and all the associated plumbing needed to connect nine large tanks with four plant production troughs. We describe these two growth methodologies in detail and report on the growth rates of all four varieties of lettuce using the vertical 'rack' and more conventional floating 'raft' approach. Finally, we report on the estimated capital and operational cost savings made possible in our production system by using these vertical growth methods.

Project Status as of: 6/30/15

In the second six months of our project we explored the potential (growth, production yields/ft2 and annual economic revenues/ft2) of Oyster Mushrooms, Broccoli and Sugar Snap Peas. We explored a single method for growing Oyster Mushrooms. We explored Broccoli growth using two methods. The first approach used an Ebb and Flow method with a lined trough filled with Hydroton grow stone, and the second approach used 2" PVC pipe. We also used two methods for Sugar Snap Pea growth. The first was 5 gallon buckets filled with our compost, and the second was the above Ebb and Flow method using a lined trough filled with Hydroton grow stone. For each of the species and approaches above we estimate the annual production yield/ft2 and the associated annual economic revenues/ft2. We also explored the implications of plant spacing on annual yeilds/ft2 and the associated economic revenues/ft2. Finally, we continued to explore new vertical rack designs and compare plant growth rate, yeilds and annual revenues per ft2 with our conventional 'float' approach. In addition, we make identical comparisons using three different seedling approaches (soil/perlite cups, soil plugs, and rockwool cubes).

Project Status as of: 12/31/15

In the third six months of the project we explored the potential (growth, production yields/ft2 and annual economic revenues/ft2) of Basil, three varieties of Bell Peppers, Ghost Peppers and Hungarian Hot Wax Peppers.

We explored a single grow method for each of these pepper varieties, However, different approaches were used for different pepper types. We used five gallon buckets filled with compost and watered daily with production system water for the Ghost Peppers. We used and ebb and flow 'wicking bed' system for Hungarian Hot Wax Peppers and a wicking bed manually watered with production system water for the three varieties of Bell Pepper. Finally, the Basil was grown on floating rafts in our plant production troughs. For each of the species and approaches above we estimate the annual production yield/ft2 and the associated annual economic revenues/ft2. We also explored the input requirements (space, water, energy, nutrients and soil) of aquaponic floating raft, hydroponic floating raft and vertical hydroponic plant growth to get a better estimate of production costs and the environmental sustainability of each approach. Finally, we describe an additional new method (Wicking Bed) of plant production.

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IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Introducing New Species

Description:

The total biomass of fish in our system determines feed input hence nutrient availability. Fish biomass is ultimately limited by Oxygen availability. Therefore, plant production will ultimately be limited by the nutrients supplied by the fish. However, economic revenues depend on the relative amounts of the different types of plants (different growth rates, nutrient demands and market prices) growing in our system. So, we plan to explore the growth and economic potential of a variety of new plant species. Tomatoes, Peppers, Strawberries, Kale, Sprouts and Mushrooms currently top our list as high potential species to explore, others will likely surface as we progress on this front.

Tomatoes will be grown two different ways. The first approach will utilize long stretches of PVC piping with two-inch holes drilled every 12 inches to hold the two-inch plastic cups containing the tomato plants. Each length of PVC will be periodically flushed with system water by pumping from trough through pipe back into trough. This will ensure the roots are constantly exposed to new nutrient rich system water from our plant production troughs. Second, tomato plants will be placed in larger 4 inch grow pots and placed in containers containing expanded shale. The shale filled container will be intermittently saturated with nutrient rich system water by a single pump (placed in production trough) running on a timer, and the water will then drain by gravity back into the production troughs. In both cases, tomato plants will be supported by vertical ropes hanging from the greenhouse rafters. Pepper and Strawberry plants will be grown in the same manner as the first approach described above for tomatoes. Kale will be grown using the same raft approach currently used for our lettuce. Sprouts will be grown in the dark using a set of vertically stacked trays that allow nutrient rich system water to spill down over them. Finally, mushrooms will be grown by adding spores to plastic bags containing sterilized wood chips. These bags will be stored in a warm damp place under our fish production tanks until mushrooms are ready for harvest. Other species and variations of these methods will also be attempted until we arrive at a reliable and economically viable method for each species.

For each new plant species we will determine growth rate per unit area, marketability and price (including the effects of seasonality) to begin to compare different species based on their revenue generation potential per square foot. In addition to improving revenue generation potential per square foot, we will also increase the variety of the food produced in our system.

Summary Budget Information for Activity 1:	**ENRTF Budget:**	**$ 66,000**
	Amount Spent:	**$ 66,000**
	Balance:	**$0**

Activity Completion Date: June 30th 2016

Outcome	**Completion Date**	**Budget**
1. *Determine plant species growth rates/unit area*	June 30th, 2015	$40,000
2. *Determine plant species production, price and marketability*	Dec 30th, 2015	$16,000
3. *Determine plant species revenue generation potential*	June 30th 2016	$10,000

Activity Status as of: 12/31/14

Tomatoes:

In the first six months of our two-year project we set up the infrastructure to grow several tomato species (Sukara, Roni, Lola, Abramson, Annalise, Brandy wine) three different ways. In the first approach tomato seedlings were transplanted into 5-gallon buckets filled with our compost. The soil surface was then covered with wood chips. These plants were watered daily, by hand, with our production system water. These plants were transplanted in May and tracked through November. Their vertical growth was supported by string hanging from the rafters. They were located along the south wall of our greenhouse.

In the second approach, tomato seedlings were transplanted into 4-inch plastic net pots containing perlite and our compost. These plastic net pots were placed in 5-gallon buckets full of ‘grow stone’ (hydroton, large perlite or expanded shale). The 5-gallon buckets had a series of small holes cut in the bottom and sides and were placed in a small trough (approximately 2’ wide, 1’ deep and 10’ long). This trough was flooded daily with production system water and then allowed to drain by into our large production troughs. These plants were also transplanted in May and tracked through November. Their vertical growth was also supported by string hanging from the rafters. They were located in the center isle of our greenhouse.

In the third approach, tomato seedlings were transplanted into 3-inch plastic net pots containing perlite and our compost. These net pots were placed in holes drilled into 4” PVC pipe. Our production system water was pumped through the 4” PVC pipe at a timed interval (the pump ran for 10 minutes every hour). These plants were also transplanted in May and tracked through November. Their vertical growth was also supported by string hanging from the rafters. They were located along the North wall of our greenhouse.

Figure's one, two and three illustrate the average total ounces harvested per plant over the June-November growth period. Looking at the different tomato types across the three growth methods their performance was quite similar with the exception of the consistently lower growth rates displayed by the large Brandy Wine species. The growth method, however, did have a large impact on growth rates. The different tomato species displayed similar growth in the 4" PVC and Compost Buckets, but far more growth was evident in the Grow Stone approach. From these initial results we would clearly recommend all tomato species be grown using the 'grow stone' approach.

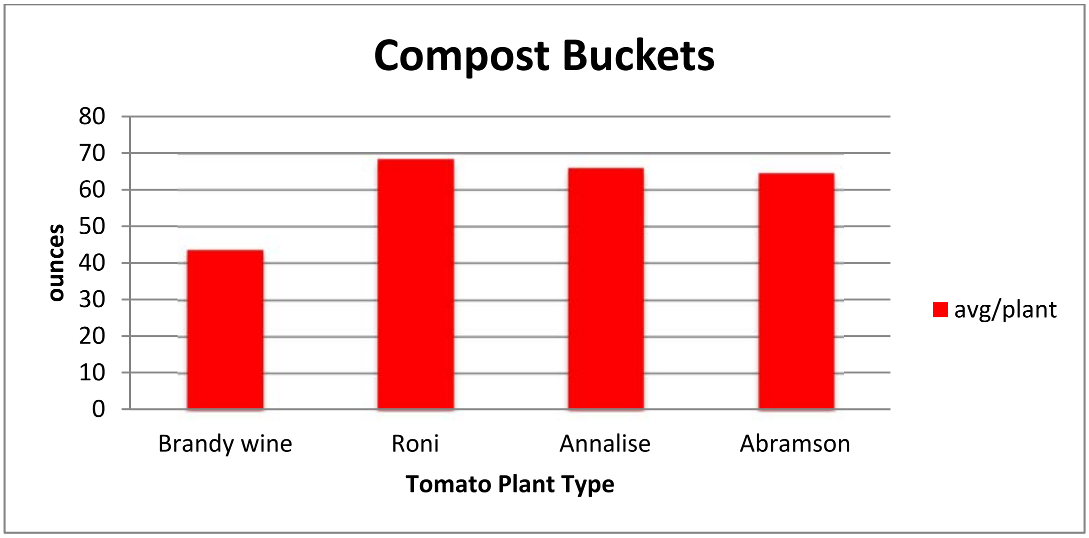


Figure 1. Average total ounces/plant harvested over the June-November 2014 growth period using the 'compost bucket' method.

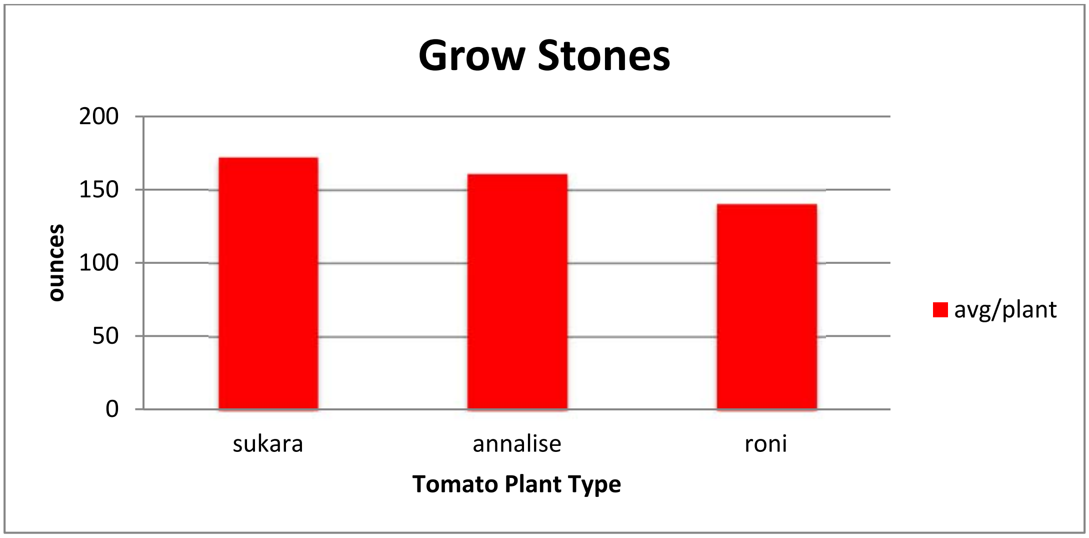


Figure 2. Average total ounces/plant harvested over the June-November 2014 growth period using the 'Grow Stone' method.

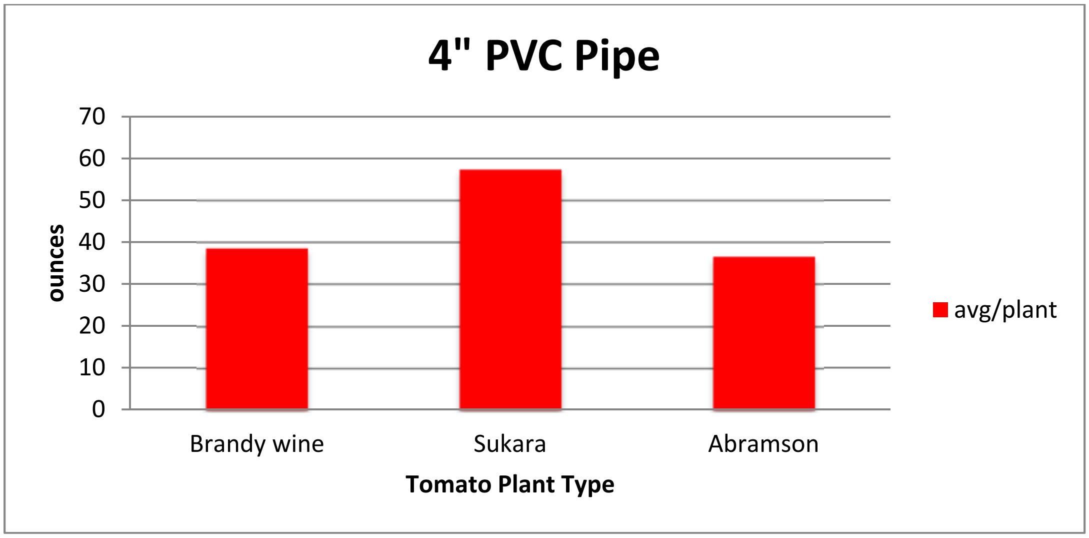


Figure 3. Average total ounces/plant harvested over the June-November 2014 growth period using the '4" PVC Pipe' method.

We were able to harvest tomatoes from June through October. All our tomatoes were sold to restaurants in Duluth and Grand Marais, MN at $3.50/lb. Figure 4 illustrates our total harvest (lbs) and sales ($). We found tomatoes to be an economically attractive crop to include in aquaponic production systems. They have a large regional market, their nutrient requirements were adequately provided by our production system water and they have a very small footprint per dollar of sales revenue. Each plant required approximately 2 square feet of space and produced an average of 160 ounces per plant (10 lbs) per 6 months using our best growth approach. So, at $3.50/lb tomatoes can generate (10 lbs * 2 months * $3.50/lb) $35.00 per square foot per year.

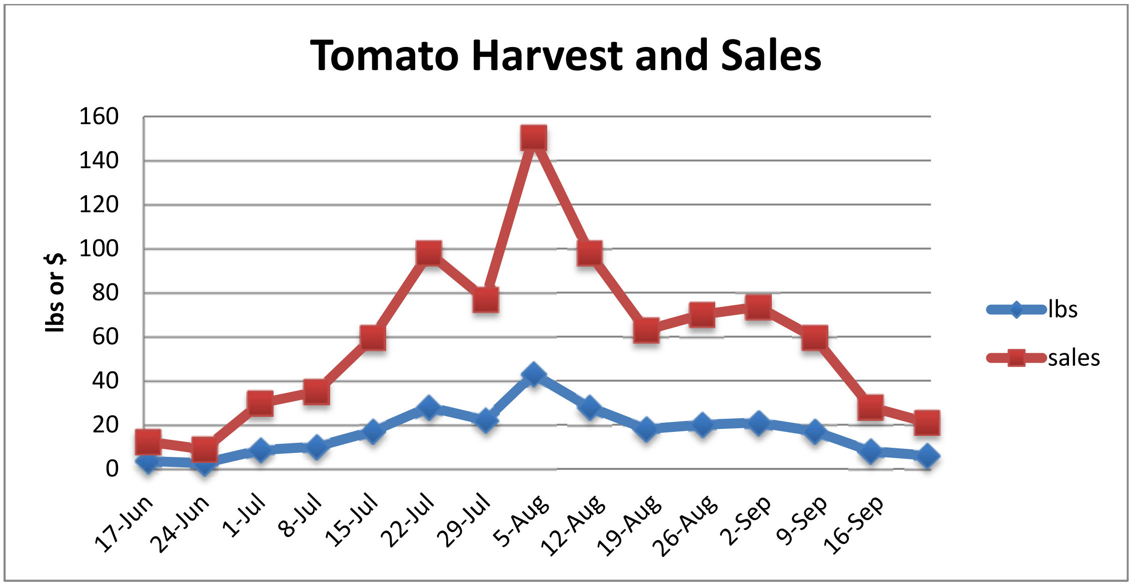


Figure 4. Tomato harvest (lbs) and Sales ($) from June through October, 2014.

Cucumbers:

In the first six months of our two-year project we also set up the infrastructure to grow two species of cucumbers (market and pickling) three different ways. We used basically the same three different growth methods as described above for the tomatoes. First, cucumber seedlings were transplanted in 5-gallon buckets filled with compost and watered daily with production system water. Second, cucumber seedlings were transplanted into 3" net pots, placed in holes drilled into 3" PVC pipe and watered by pumping production system water through pipe. Third, a lined box (1' x 1' x 12') was constructed with 2" x 8" boards and filled with grow stone (hydroton, large perlite and expanded shale). Cucumber seedlings were transplanted in 3" net pots, placed in this grow stone bed and watered with production system water intermittently pumped into the grow stone bed. Our cucumbers were planted in June, transplanted in July and harvests began in early August and continued through September. Figures 5 and 6 illustrate the average production per plant in each of the three growth methods for both our cucumber types.

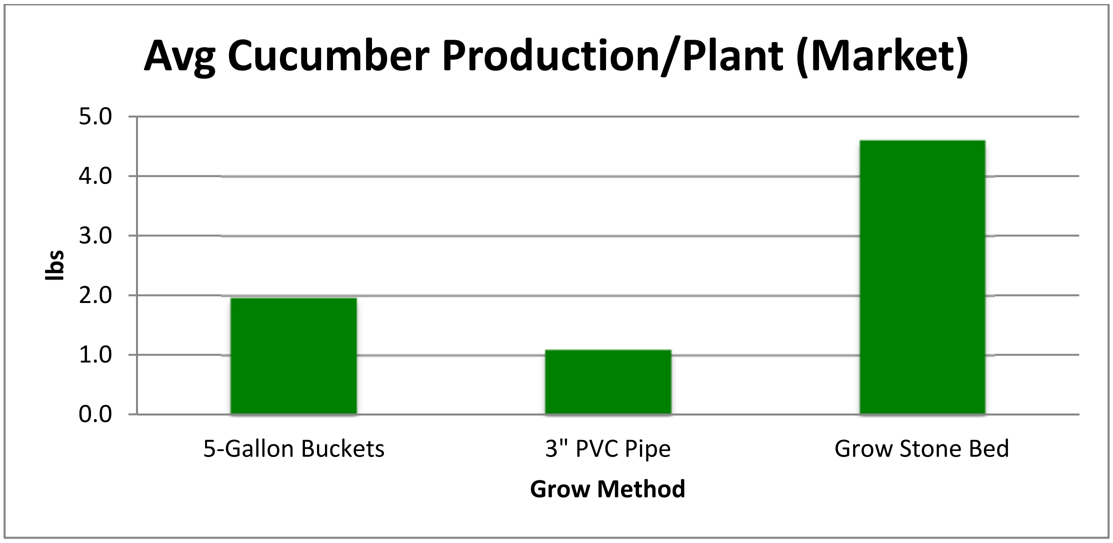


Figure 5. Average cucumber production per plant in each of the three growth methods for Market cucumbers.

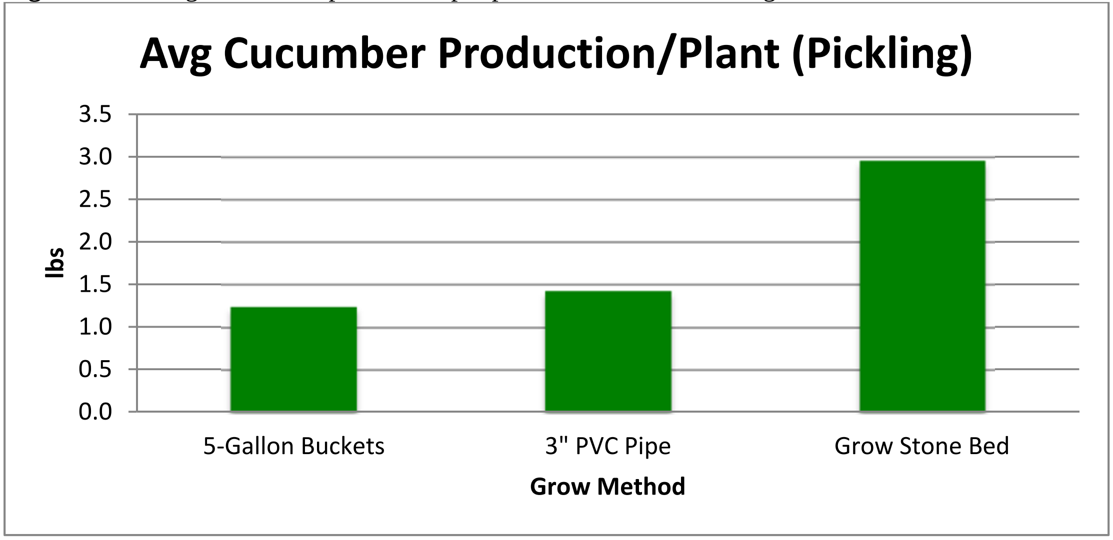


Figure 6. Average cucumber production per plant in each of the three growth methods for Pickling cucumbers.

Both Market and Pickling Cucumber species demonstrated their highest production rates using the Grow Stone Bed approach. Market Cucumbers were more productive than Pickling Cucumbers and were more popular with our produce buyers. We recommend Market Cucumbers using the Grow Stone Bed methodology.

Figure 7 illustrates weekly cucumber harvest and sales in August and September of 2014.   Weekly harvests ranged from 7 to 30 lbs, and sales ranged from $10 to $45. We sold our cucumbers to a variety of restaurants and grocery stores for $1.50/lb. Each cucumber plant required 2 square feet of floor space and produced 4.5 lbs per plant in our two month grow period. Therefore, at $1.50/lb our cucumbers are capable of generating (4.5 lbs/plant * 6 months * $1.50/lb) $20.25 per square foot per year.

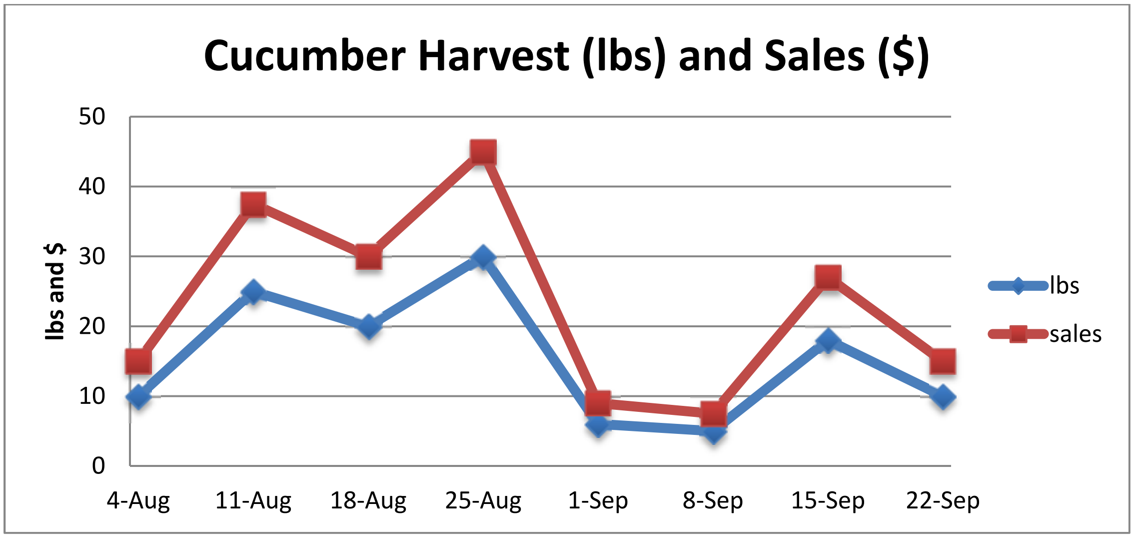


Figure 7. Cucumber harvest and sales from August and September of 2014.

Activity Status as of: 6/30/15

From January – June of 2015 we explored the potential for growing Oyster Mushrooms, Broccoli and Sugar Snap Peas using a variety of methods.

1. *Oyster Mushrooms*

There are several dark, warm and moist places in our facility that provide excellent habitat for the growth of mushrooms. Also, mushrooms provide the potential for another source of revenues without taking up valuable floor space in the sun. We used straw substrate as a growing medium for Pearl Oyster Mushrooms. On 3/6/15 we pasteurized the straw by soaking for one hour in a 50-gallon drum of approximately 170°F water. The straw was then removed from the heated water and cooled on a sanitary surface to room temperature. Pearl oyster sawdust spawn was added to the substrate, and the straw-spawn mixture was packed tightly into plastic tubes (plastic bags) of approximately four feet in length and eight inches in diameter. In this process, about 7 ½ lbs of dry weight straw was used per tube (or approx. 20 lbs of saturated straw) along with 1¼ cups of pearl oyster sawdust spawn.

On 3/14/15 four of these plastic tubes (bags) were hung up vertically in a 2,000 gallon (8’ diameter x 5’ depth) plastic tank enclosure with plastic over the top. Holes (approximately 1” in diameter) were punched in the bags every 3 – 4 inches. The temperature of the enclosure was maintained at about 70 degrees along with 40% humidity. Misting of the bags every few days helped to retain moisture for mushroom development and keep the humidity around 40%. The first signs of mycelium growth occurred on 3/18/15, and the first harvest occurred on 4/13/15. The harvest schedule and weights are found in table 1.

Table 1. Oyster Mushroom harvest dates and weights.

Harvest Date	Harvest Weight (lbs)
4/13/15	1.4
4/15/15	2.1
5/27/15	2.36
6/6/15	0.25
6/8/15	0.31
6/12/15	0.26
6/15/15	0.35
6/17/15	0.24
6/19/15	0.53
TOTAL	**7.8**

Each Oyster Mushroom Tube requires approximately 1 ft2 of growing space. 4 of these tubes yielded approximately 8 pounds in 8 weeks. This equates to 1lb/week or 1/4lb per tube per week. Therefore, each ft2 of growing space can yield approximately 1/4lb/week. Our Oyster Mushrooms sell for approximately $2/lb yielding $.50/week. Using this method, total

Oyster Mushroom revenues are expected to be $26/ft2/yr. These are significant revenues given the fact that they do not require sunlit space.

2. *Broccoli –Hydroton grow medium trough vs. 2” PVC*

We planted Broccoli (type) on March 15th, 2015. We transplanted broccoli plants into 2” net pots containing a mix of perlite and compost, and used these plants to test two different growth methods. First, we placed 8 plants into a 2’ x 12’ 8 inch deep lined trough filled with Hydroton expanded clay pellates on April 12th, 2015. The 2” net pots containing our transplants were simply buried into the grow stone up to the top of the net pot. This trough was connected to a 20-gallon nutrient reservoir tank, and nutrient was intermittently (run time of 15 minutes per hour) pumped into trough and then allowed to flow back into nutrient reservoir by gravity. The water chemistry parameters were kept as close to following as possible: Temperature of 65 degrees F; pH of 6.5; Oxygen of 7 ppm; TDS of 500 ppm. The broccoli plants appeared to grow very well in this environment, by day 60 we saw our first heads forming, and by June 5th, 2015 we harvested the heads from our first 4 plants. These heads ranged in weight fronm 4.5 – 6.4 ounces. We are now witnessing the growth of secondary heads and expect to harvest 3-4 smaller heads (1-3 ounces) from each plant over the next few months. Each plant requires approximately 1.5 ft2 to mature. Therefore, we expect 4 harvests of approximately 12 ounces per plant per year. With an area requirement of 1.5 ft2/plant that equates to 9 ounces/ft2/yr. This broccoli sells for $.25/ounce. Therefore, total broccoli sales using this method equal $2.25/ft2/yr.

Second, we placed 12 of our April broccoli transplants (2” net pots) into 2” holes drilled into a 20’ line of 4” PVC pipe. This PVC pipe was connected to another 20- gallon nutrient reservoir and nutrient was intermittently (run time of 15 minutes per hour) pumped through the pipe and allowed to drain back into the nutrient reservoir by gravity. The water chemistry parameters were kept as close to the levels indicated above as possible. The broccoli plants also appeared to grow well in this environment. By day 68 we saw our first heads forming, and by June 12th we harvested the heads from our first 3 plants. These heads weighed from 3.9 to 5.4 ounces. Therefore, using the PVC method the heads took approximately one week longer to form and weighed slightly less than those grown in Hydroton troughs. We are now witnessing the growth of secondary heads and expect to harvest 3-4 smaller heads (1-3 ounces) from each plant over the coarse of the growing season. Each plant requires approximately 1.5ft2 to mature. Therefore, we expect 4 harvests of 10 ounces per plant per year. With an area requirement of 1.5 ft2/plant that equates to 7.5 ounces/ft2/yr. This broccoli sells for $.25/ounce. Therefore, total broccoli sales using this method equal $1.88/ft2/yr.

3. *Sugar Snap Peas – 5 gallon compost buckets vs. grow medium trough*

We planted sugar snap peas (type) on January 10th, 2015. These plants were transplanted into 2” net pots containing perlite and compost on February 1st, 2015, and used to test two different growth methods. First, we placed 10 plants into a 2’ x 12’ 8 inch deep lined trough filled with Hydroton expanded clay pellates on February 4th, 2015. The 2” net pots containing our transplants were simply buried into the grow stone up to the top of the net pot. This trough was connected to a 20-gallon nutrient reservoir tank, and nutrient was intermittently (run time of 15 minutes per hour) pumped into trough and then allowed to flow back into nutrient reservoir by gravity. The water chemistry parameters were kept as close to following as possible: Temperature of 62 degrees F; pH of 6.0; Oxygen of 8 ppm; TDS of 400 ppm. The sugar snap pea plants grew very well in this environment. We witnessed the first flowers by February 14th, and harvested our first sugar snap peas on March 2nd, 2015. Total harvest from these ten plants averaged 20.2 ounces per week. Each plant required only approximately 1ft2 of space as the vine grew vertically from its contact with the growth medium. This equates to approximately 2 ounces/ft2/week or 104 ounces/ft2/yr. We were able to maintain these weekly production yields through May of 2015, and then they began to taper off. If the plants were cycled every two months these production values could be maintained throughout the year. Our sugar snap peas sell for $.25/ounce. Therefore, one can expect annual sales revenues of $26/ft2/yr from sugar snap peas grown in this manner. This has the potential to be a highly profitable crop in a hydroponic greenhouse production system.

Second, we placed 10 plants into 5-gallon plastic buckets filled with our compost and topped with wood chips on February 4th, 2015. The 2” net pots containing our transplants were simply buried into the compost mix up to the top of the net pot and then approximately 1 inch of wood chips were sprinkled over the top. These buckets were watered once per day with water from the nutrient reservoir connected to the trough described above. Therefore, the water chemistry was the same as above (Temperature of 62 degrees F; pH of 6.0; Oxygen of 8 ppm; TDS of 400 ppm). The sugar snap pea plants also grew very well in this environment. We witnessed the first flowers by March 10th, and harvested our first sugar snap peas on March 1st, 2015. Total harvest from these ten plants averaged 22.2 ounces per week. Each plant required only approximately 1ft2 of space as the vine grew vertically from its contact with the growth medium in the buckets. This equates to approximately 2.2 ounces/ft2/week or 106 ounces/ft2/yr. We were able to maintain these weekly production yields through May of 2015, and then they began to taper off. If the plants were cycled every two months these production values could be maintained throughout the year. Our sugar snap peas sell for $.25/ounce. Therefore, one can expect annual sales revenues of $27/ft2/yr from sugar snap peas grown in this manner. This has the potential to be a highly profitable crop in a hydroponic greenhouse production system whether grown simply in compost filled buckets or in the more complicated trough containing Hydroton grow stone.

Activity Status as of: 12/31/15

a. Basil (floating rafts)

On July 2nd, 2015 two hundred basil seeds were planted into a 200-compartment plug flat. The plug flat was filled with our compost and one seed was planted into each compartment. The plug flat was watered daily (with our nutrient rich production system water) and kept under 4' tubular compact fluorescent lights (approximately 200 micro insteins/m2/sec) at a temperature of 70 degrees F and at 40-60% humidity. On August 3rd, 2015 each basil plant plug (averaging 8.1 cm in height) was transplanted into a two-inch net pot and placed onto a 36-hole 2' x 4' 1.5 inch rigid polystyrene float. We used 144 plants to fill four 36-hole floats. On August 14th we conducted our first harvest by trimming the top section of the plant. We conducted 11 weekly harvests from these four floats containing the 144 plants from 9/14/15 – 10/23/15. (Table 1).

Date	Harvest (oz.)
8/14/15	10.2
8/21/15	14.7
8/28/15	26.3
9/4/15	38.5
9/11/15	43.1
9/18/15	47.2
9/25/15	46.8
10/2/15	49.6
10/9/15	43.8
10/16/15	40.2
10/23/15	37.1

Our basil was sold in .75 ounce clamshells for $1.50 per clamshell. Each clamshell actually contained an average of .7 ounces of basil. Therefore, we received $2.14 per ounce of basil or $34.24 per pound. Over the 11-week period we averaged 36.14 ounces per weekly harvest or $77.33 per week. The four floats were a total of 32 ft2. Therefore, we averaged $2.42/ft2 per week from basil. Extrapolated over a 52-week period one can expect a $125.84/ft2/yr gross return from basil grown in this manner. Basil has proven to be our most profitable crop, but it is difficult to keep it healthy year-round. Designing a low-energy requiring system to keep an optimal year-round temp environment for basil is the subject of our next 6 months of research.

b. Ghost Peppers (compost buckets)

We planted several Ghost Pepper plants on March 13, 2015. These plants were transplanted into 4" x 4" x 6" pots and placed under High Pressure Sodium grow lights (12 hour photoperiod) in our indoor climate controlled seedling room until April 14th, 2015. They were then transplanted into 10-gallon compost filled containers and moved out to the greenhouse. The harvest data from a single plant occupying 4 ft2 of floor space are reported below.

Ghost Peppers (extremely hot red pepper)

Date	Weight (lbs)
7/27	1.2
8/5	.5
8/12	1.1
8/21	.7
8/28	.2
9/5	1.4
9/12	.9
9/20	.6
9/28	.3
10/6	.1
10/15	.8
10/22	.2
11/1	.1

Our Ghost Peppers sold for $25/lb to a local restaurant. The weekly yield from a single plant occupying 4ft2 of floor space averaged .8 lbs, or .2 lbs/ft2/week. That equals $5.00/ft2/week or $260/ft2/yr. Ghost Peppers are a very high potential source of revenues, and we will explore them further.

c. Hungarian Hot Wax Peppers (compost buckets)

We planted several Hungarian Hot Wax Pepper plants on March 13, 2015. These plants were transplanted into 4” x 4” x 6” pots and placed under High Pressure Sodium grow lights (12 hour photoperiod) in our indoor climate controlled seedling room until April 14th, 2015. They were then transplanted into a 10-gallon compost filled containers and moved out to the greenhouse. The harvest data from a single plant occupying 4 ft2 of floor space are reported below.

Hungarian Hot Wax Peppers (hot red peppers)

Date	Weight (lbs)
7/27	2.3
8/5	.8
8/12	1.5
8/21	.9
8/28	.3
9/5	1.2
9/12	1.4
9/20	.6
9/28	.9
10/6	1.4
10/15	1.7
10/22	1.4

Our Hungarian Hot Wax Peppers sold for $8/lb to a local restaurant. The weekly yield from a single plant occupying 4ft2 of floor space averaged 1.1 lbs, or .253 lbs/ft2/week. That equals approximately $2.00/ft2/week or $104/ft2/yr. Hungarian Hot Wax Peppers are also a very high potential source of revenues, and we will explore them further.

Final Report Summary:

As described in our three previous Semi-annual reports we examined several common produce species to determine their potential yields, local markets and sales revenues. We also explored various methods for producing these crops within our controlled environmental agriculture (CEA) system. Focusing on the approaches that generated the best production yields, we calculated the total annual revenues per square foot of greenhouse space to facilitate comparison across the various produce species we explored. The results of this work are illustrated in Table 1.

Table #1. Trial dates, annual yields per square foot, market price obtained and annual revenues per square foot of greenhouse production space for a variety of popular produce varieties.

Variety	Date	yield/ft2	$/yield	$/ft2
Tomatoes	6/1-10/1 ’14	10 lbs	$3.50/lb	35
Cucumbers	8/1-10/1 ’14	13.5 lbs	$1.50/lb	20.25
Sugar snap peas	1/1-6/1 ’15	115.44 oz	$.25/oz	28.86
Oyster Mushrooms	3/1-7/1 ’15	13 lbs	$2.00/lb	26
Broccoli	3/9-8/9 ’15	9 oz	$.25/oz	2.25
Bell Peppers	3/9-9/9 ’15	7.8 lbs	$3.00/lb	23.40
Hungarian Hot Wax	3/9-10/1 ’15	7.15 lbs	$8.00/lb	52
Ghost Peppers	3/9-10/1 ’15	5.2 lbs	$25/lb	130
Basil	7/2-11/1 ’15	58.7 oz	$2.14/oz	125.84
Lettuce	1/1-11/1 ’15	9.6 lbs	$10.6/lb	101.76

We found that all of the above crops (with the exception of broccoli) have the potential to generate significant annual revenues. Experience has taught us that there are many considerations beyond annual revenues per square foot of growing space when selecting the optimal varieties. The most critical include the ability to consistently grow the variety year-round in our cold winter climate, the size of the local market, and the labor costs associated with planting, transplanting and harvest. For example, the two hot pepper varieties (Hungarian Hot Wax and Ghost), although they have the potential to generate high revenues/ft2 and require relatively small labor costs they are very difficult to grow year-round and have a limited market in high-end restaurants. Basil is also very difficult to grow year-round and has a smaller local market. Our conclusion, all things considered, is that lettuce is the best potential crop given its high price (if sold in 5 or 10 oz clamshells), large market, consistent year-round growth and manageable labor costs. We would also suggest producing supplemental limited quantities of seasonal hot peppers and basil.

ACTIVITY 2: Exploring New Growth Methods

Description:
Currently we are growing our fish in tanks, and our produce (lettuce and basil) in rafts floating on the surface of shallow troughs (6 inches deep) in our greenhouse. We have four 16 x 48 foot troughs. This is enough surface area for approximately 600 heads of lettuce and 40 lbs of basil per week. We are planning to explore two new vertical growing methods and compare the results with our conventional 'raft' approach. These new vertical methods have the potential to support up to four times the production per square foot while lowering operational costs (labor, heating and electricity), and allowing us to move our fish out to the troughs.

Vertical columns will be made using standard 1.5 inch PVC piping suspended from the greenhouse rafters above the plant production troughs. Two elbows will be placed opposite one another every 6 inches up the 6-foot vertical pipe to hold plastic plant cups. Water will be intermittently pumped through these vertical columns (in on top and out through bottom) in a manner that keeps the plant roots bathed in the nutrient rich fish wastewater within the vertical column. We will also construct long lengths of standard 2 inch PVC pipe with 1.5 inch holes drilled in top side of pipe every 12 inches. These PVC pipes will be hung (at a slight grade) from the rafters above the troughs, and water will be intermittently pumped through them to keep plant roots submerged inside the piping. The water from both the vertical and horizontal piping will drain directly back into the trough beneath them.

We plan to compare the density, growth rates and relative health of a variety of plants (lettuce, basil, Kale, strawberries, peppers) grown in the PVC piping described above with our plants currently growing on the floating rafts. We will construct the columns and repeat the comparisons numerous times (to capture any seasonality affects) with a wide variety of plants. In addition, we plan to estimate the potential revenue increases and capital cost reductions associated with these new potential plant-growing methodologies.

Finally, if the plants grow well in the vertical and horizontal PVC piping, and the floating rafts can be eliminated we plan to explore the possibility of moving our fish into a single greenhouse trough beneath the vertical/horizontal PVC columns. If the fish are as healthy, can be stocked as densely (without using up available Oxygen) and grow as quickly in these troughs, then we could eliminate a great deal of water along with the heating and pumping costs required. We could also significantly decrease the needed square footage of the building along with all the fish tanks and plumbing that connects them. This arrangement also opens the door to far cheaper heating and filtration options.

Summary Budget Information for Activity 2:		
	ENRTF Budget:	**$ 110,000**
	Amount Spent:	**$ 110,000**
	Balance:	**$ 0**

Activity Completion Date: 6/30/16

Outcome	**Completion Date**	**Budget**
1. *Construct and test vertical and horizontal PVC columns*	12/31/14	$30,000
2. *Determine density/plant growth rates/health using these columns*	6/30/15	$20,000
3. *Compare plant density/growth rates/health with current 'raft' approach*	12/31/15	$10,000
4. Alter single trough (heat/filtration) to support fish growth	12/31/15	$20,000
5. Determine fish density/growth rates/health in trough under columns	6/30/16	$10,000
6. Compare with fish density/growth rates/health in current tanks	6/30/16	$10,000
7. Estimate revenue gains/cost savings of new growth methods	6/30/16	$10,000

Activity Status as of: 12/31/14
We explored the possibility of growing our plants vertically in horizontal 'racks' by comparing their growth rates with those of our current floating 'raft' plants. Most aquaponic operations rely on floating 'rafts', but growing

vertical allows more production per square foot and opens the possibility of moving fish from indoor tanks to plant troughs in the greenhouse. These changes would considerably reduce capital and operational costs.

We designed and installed several vertical 'racks' using ten, ten-foot lengths of 2" PVC pipe hanging from greenhouse rafters in a stacked, switch backed pattern. 12 2" holes are drilled into each ten-foot length of 2" PVC pipe. Our production system water was pumped to the top of the vertical rack, and flowed by gravity through these vertically stacked PVC pipes. The plants grew with their roots soaked in this water. Figure 8 illustrates this new vertical 'rack' approach. In the more conventional floating 'raft' approach 18 2" holes are drilled into 2' x 4' sheets of 1.5" rigid foam insulation. Plants are placed in each hole with roots dangling in production system water below floats. Figure 9 illustrates the more conventional floating 'raft' approach. Both approaches use 2" plastic net pots containing perlite, compost and lettuce transplants.

Figure 8. Vertical 'Rack' production method

Figure 9. Horizontal floating 'raft' production method

We monitored plant growth rates in August/September and compared the growth rates of these vertical 'racks' with those in our floating 'rafts'. Four different lettuce varieties were compared: Bibb, Romaine, Green Leaf, and Red Leaf. We used a two-sample t-test to compare the difference of the means representing the two growth approaches. For each variety of lettuce, we had a sample size of 18 plants per method of growing.

Table 1 indicates the basic summary statistics for each lettuce variety and Table 2 indicates the actual statistical significance determination. For each variety of lettuce, we had the same hypothesis: The average weight of a head of lettuce on the rafts is equal to the average weight of a head of lettuce on the racks.

Table 1. Summary Statistics for each lettuce variety

	Summary of Statistics (in grams)							
	Bibb		Romaine		Green Leaf		Red Leaf	
	Rack	Raft	Rack	Raft	Rack	Raft	Rack	Raft
Mean	83.27	116.56	73.52	118.63	101.23	161.46	69.48	97.87
Standard deviation	36.37	47.22	18.56	52.07	22.41	17.24	13.71	19.7
Median	87.15	116.5	75.95	117.1	99.5	158.75	68.15	95.15
Minimum weight	1	27.2	36.2	54.9	68.7	135.2	41.3	64.5
Maximum weight	125.4	205.1	105.1	296.1	163.3	201.7	92.3	127.7

Mean: The average weight in grams of the 18 heads of lettuce.
Standard Deviation: Represents the 'spread' or 'dispersion' of the data.
Median: Represents the midpoint of the range of values where 50% of the data lie below and above the median.

Table 2. Results for each lettuce variety

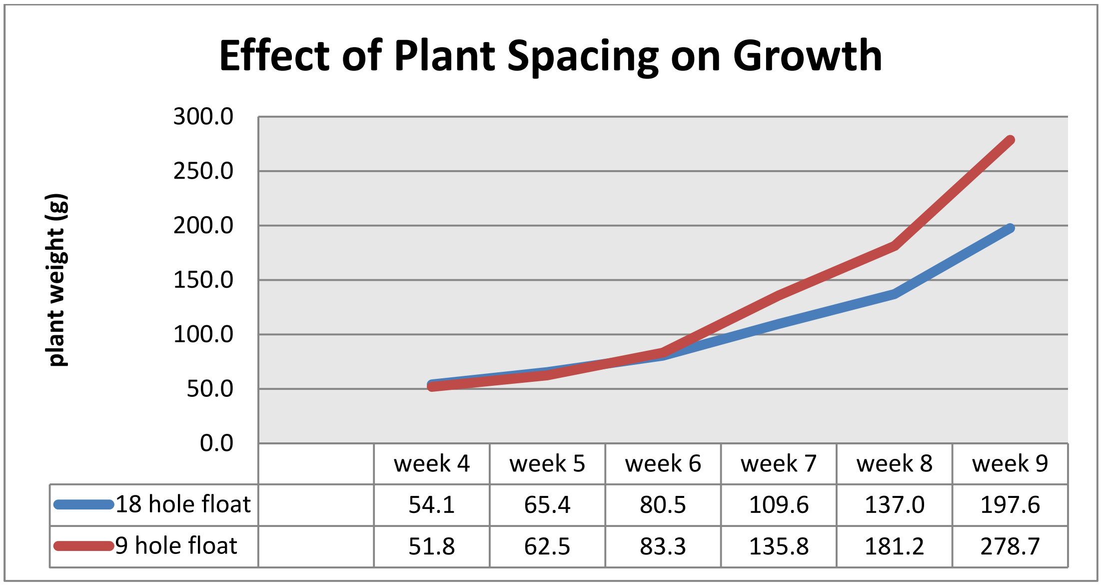
	Results of Experiment: Racks vs Rafts							
	Bibb		Romaine		Green Leaf		Red Leaf	
p-value	0.0236		0.0015		<.0001		<.0001	
95% confidence interval of $\mu_{Rafts} - \mu_{Racks}$	4.74	61.84	18.64	71.59	46.7	73.78	16.89	39.89

These results were found using the R statistical package. To interpret the results, we use our Bibb variety as an example. The p-value comes from the t-test and for Bibb it came out to be .0236 which is less than .05 (we choose .05 because we want to be 95% confident about the results), thus there is significant evidence that the difference between the two sample means is not zero. Therefore, we reject the hypothesis that the two sample means are equal. Also, we are 95% confident that the difference of the average weight from the rafts and the average weight from the racks falls in the interval of 4.74 grams and 61.84 grams. Thus, the Bibb growing on the rafts did significantly better than the Bibb growing on the racks. Tables 1 and 2 show that the floating 'raft' approach did significantly better than using the vertical 'racks' for all four varieties of lettuce compared. We are now designing and installing new vertical racks in an attempt to improve their performance, so we can take full-advantage of the vast economic benefits provided by this approach.

Activity Status as of: 6/30/15
From January to June of 2015 we focused our efforts on exploring the growth and economic ramifications of plant spacing, and we continued to explore vertical vs. horizontal plant growth.

1. *Lettuce Spacing*

The number of mature lettuce heads that can be produced per unit area is dependent on spacing. If the individual lettuce plants are crowded too close together they leaves of each plant will eventually be stunted as the overlapping plants compete for light. If the individual plants are growing too far apart then valuable space is being wasted. The key is to keep the plants together as close as possible without the growth limiting effects of crowding. In an effort to determine this optimal spacing we monitored the weight of lettuce heads grown with two different spacing configurations. Two 2' x 4' (8 ft2) pieces (floats) of 1.5" rigid polystyrene were used for this experimentation. Nine 2" holes were drilled (spaced equally apart) to support nine lettuce plants on the first float, and 18 2" holes were drilled (spaced equally apart) to support 18 lettuce plants on the second float. These two 2' x 4' floats were filled with 4 week old lettuce plants (New Red Fire), and placed next to one another in our 16' x 48' troughs. For the next five weeks all nine of the 9-hole float plants and every other plant (9 total) on the 18 hole floats were weighed once per week. The plants encountered the same light levels and water chemistry: Temperature of 70 degrees F; pH of 6.6; Oxygen of 6 ppm; TDS of 300 ppm.



	week 4	week 5	week 6	week 7	week 8	week 9
18 hole float	54.1	65.4	80.5	109.6	137.0	197.6
9 hole float	51.8	62.5	83.3	135.8	181.2	278.7

Figure 1. The growth of New Red Fire Lettuce plants on 9 hole and 18 hole floats. The holes were spaced equally, so plants were twice as crowded on the 18 hole floats.

Figure 1. illustrates the growth of these lettuce plants on each float over the 5 week period. It is clear that the plants enjoying a greater space between them (less crowding on the 9 hole floats) grew much larger than the plants on the 18 hole floats. It is also worthy to note that the plant growth differences did not appear until week six (the point at which the lettuce on the 18 hole float began to crowd). This suggests that maximum plant growth (and utilization of space) can likely be found at a spacing configuration somewhere between 9 and 18 holes per 2’ x 4’ float. However, it is important to note that although the individual plants on the more crowded 18 hole floats were smaller, the total biomass harvested from the 8 ft2 18 hole float was considerably larger (3557 g) than that from the 8ft2 9 hole float (2508). Therefore, if selling lettuce by the pound it is optimal to go with the 18 hole floats, and if trying to grow large beautiful heads it is better to go with the 9 hole floats.

Using the 18 hole floats we were able to harvest 3557 g/8ft2/week. The weight of the soil/perlite net pot (approx. 50 g) must be subtracted from this number to get actual plant weight (3557 - (18*50) = 2657 g/8ft2/week). In our 16’ x 48’ troughs (plants require 4 weeks in the trough to reach maturity) we are able to harvest 24 of these 18 hole floats per week for a total of 63,768 g/week or 3,315,936 g/yr. Dividing that production yield by the square footage of our troughs (768 ft2) totals 4318 g/ft2/yr or 9.6 lbs/ft2/yr. We sell our lettuce for $4.50/lb. Therefore, our total annual revenues from lettuce sales equal $42.80/ft2. Lettuce is by far our most lucrative crop to date.

2. *Racks vs. floats*

We continued to explore new vertical rack designs and the economic implications of growing our lettuce plants in vertical racks rather than the horizontal floats (‘rafts’) described above to make far better use of our limited floor space. To do this we grew lettuce plants on horizontal floats (rafts) and two kinds of vertical racks while attempting to hold all critical growth parameters (temp, pH, nutrients (TDS) light etc…) as equal as possible. These plants were weighed once per week for five weeks, the results were compared and the economic ramifications for each method were calculated.

We have experimented with a variety of vertical rack designs, and consider only the two most effective designs in this report. The first vertical rack design consists of an 8’ x 8’ box frame made with 1” x 4” green treated lumber. ¼” Holes are drilled into the three vertical 8’ 1” x 4” every 3”, and wooden pegs placed in the holes are used two support the 10’ lengths of 2” PVC pipe that run parallel to the floor. Holes (1”) are drilled into these PVC pipes spaced every 6” along their length. Plants are placed into these holes, and their roots are free to dangle in the water running through the pipes. The water is pumped from a 60-gallon nutrient reservoir tank on the floor into a 5-gallon plastic bucket suspended above the vertical rack. The base of the bucket has several barbs that connect to ¼” irrigation tubing which feeds the top PVC pipe in each rack. The water then flows by gravity through the eight 10’ lengths of PVC pipe and then drains into the nutrient reservoir after exiting the bottom PVC pipe on each rack. The racks contain 16 PVC pipes with 20 holes per pipe for a total of 320 plants per rack. A set of four racks allows ample growing time for a harvest of 320 plants/week from each rack set. Wheels are attached to the top of each rack and mounted on a track, so that the racks can easily be moved to control spacing between them. See Figure 2 for a photo of these vertical racks.

Figure 2. Photo of our vertical lettuce racks.

The second vertical rack design we have experienced some consistent success with are what we call ‘A Frames’. In this approach two 8’ green treat 2” x 4”’s are joined at the top with a hinge that allows us to adjust the space between the 2” x 4”s at the base. Three of these are used to support the 2” PVC pipes. As described above, ¼” holes are drilled into the three 2” x 4” ‘A Frame’ supports every 3”, and wooden pegs placed in the holes are used two support the 10’ lengths of 2” PVC pipe that run parallel to the floor. Holes (1”) are drilled into these PVC pipes spaced every 6” along their length. Plants are placed into these holes, and their roots are free to dangle in the water running through the pipes. The water is pumped from a 60-gallon nutrient reservoir tank on the floor into a 5-gallon plastic bucket suspended above the ‘A Frame’. The base of the bucket has several barbs that connect to ¼” irrigation tubing which feeds the top PVC pipe in each ‘A Frame’. The water flows by gravity through the eight 10’ lengths of PVC pipe and then drains into the nutrient reservoir after exiting the bottom PVC pipe on each ‘A Frame’. A Single ‘A Frame’ contains 16 PVC pipes with 20 holes per pipe for a total of 320 plants. A set of four ‘A Frames’ allows ample growing time for a harvest of 320 plants/week from each set. See figure 3 for a photo of these ‘A Frames’.

Figure 3. Photo of our ‘A Frame’ lettuce racks.

Figure 4 illustrates the results of the plant growth achieved using the two vertical approaches described above and the conventional horizontal float (raft) approach.

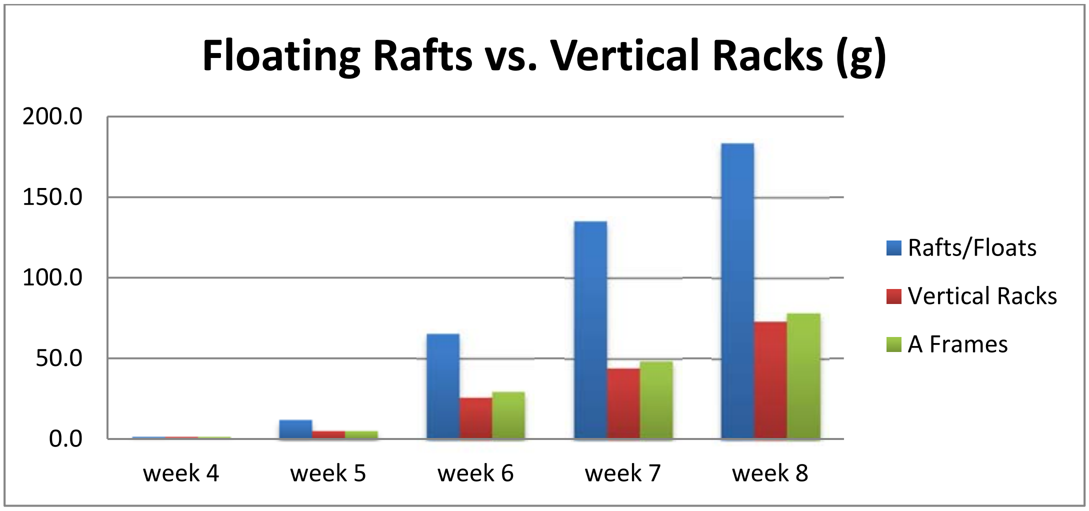


Figure 4. Weekly lettuce plant weights (g) using the three (floating rafts; vertical racks and A frames) growth methods described above. Starting at week 4 and continuing until harvest at week 8 using green romaine lettuce. All weights in grams. Experiment ran from 3/2 -4/5 of 2015.

We have repeated these experiments several times, and have always found similar results. We consistently achieved our best growth rates and lettuce head sizes using the conventional 'raft' approach. The 'A Frame' approach was second and the 'vertical rack' approach was a close third.

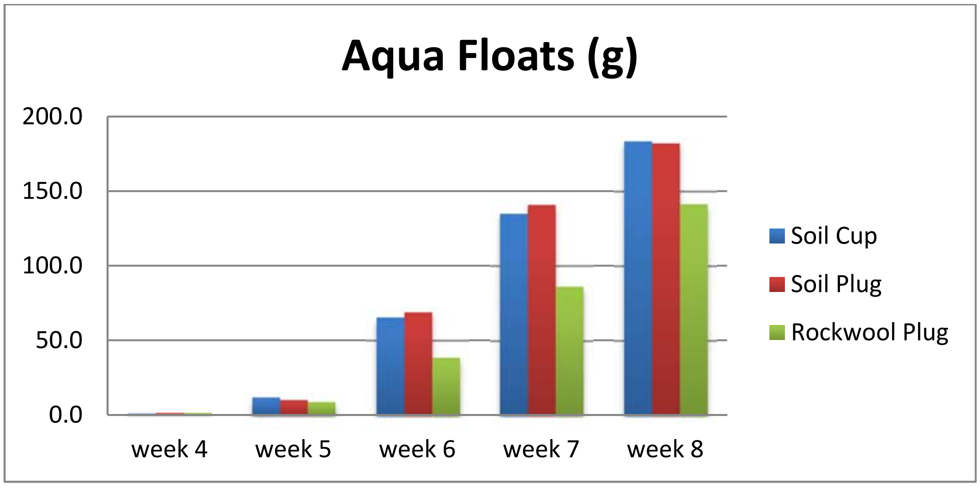
However, the economic implications of achieving vertical plant growth are significant. Using the data from our spacing experiment above the conventional floating raft approach generated revenues of $42.79/ft2/yr. Using the more recent data set illustrated in figure 4 the same 'raft' method generated $38.73/ft2/yr. In comparison, although the average lettuce head size at harvest was considerably smaller using the Vertical Rack Method (73.3 vs 133.6 g/head) this method generated far more annual revenue/ft2/yr ($62.96 vs. $38.73) because of the far better use of floor space that vertical rack growth allows. Finally, the 'A Frame' method generated the most annual revenue/ft2/yr ($67.51) due to its slightly larger average head size.

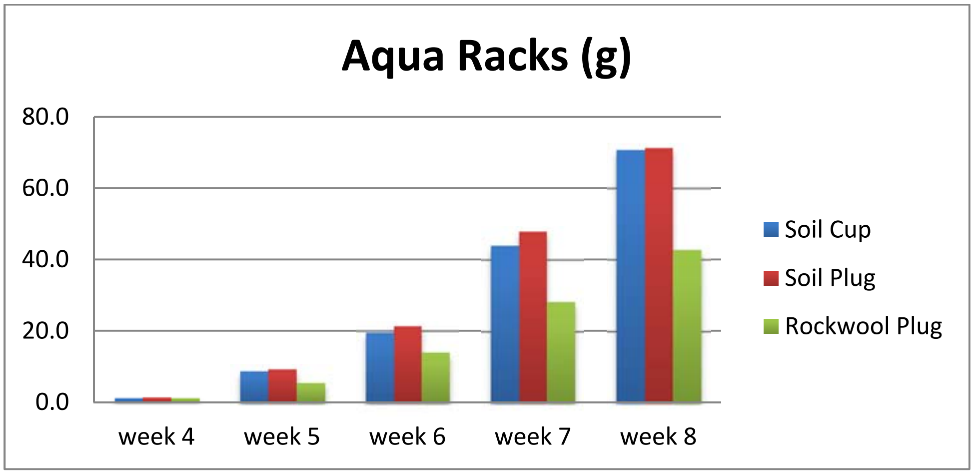
3. Soil vs. Rockwool

We also began to explore three different seedling methods: 1. Soil Plugs; 2. Rockwool Plugs; and 3. Traditional 2" net pots with ¾ perlite on bottom and ¼ soil on top. The soil plugs consist of a conventional seedling tray with 200 compartments/tray. Each compartment is filled with about one cubic inch of soil. One seed per compartment is planted, and left in the dark for a couple days to germinate. When the seedlings are one week old those from compartments with more than one seed are moved into compartments with no seedlings to better ensure one seedling per compartment. The seedlings are kept under the lights in a climate controlled seedling room until they are 3 weeks old. At three weeks of age the soil plugs (potting soil, plus root and seedling) are transferred into 2" net pots and placed onto 2' x 4' floats containing 156 holes. They spend 2 weeks in these floats and are then transferred to their final grow out spot (vertical racks, A Frames, or floats).

The rockwool plugs consist of a rockwool sheet the size of a conventional seedling tray containing 256 holes. One seed per hole is planted, and left in the dark for a couple days to germinate. The seedlings are placed under the lights in a climate controlled seedling room until they are 3 weeks old. At three weeks of age the rockwool sheets are broken up into the 256 individual rockwool plugs and transferred into 2" net pots and placed onto 2' x 4' floats containing 156 holes. They spend 2 weeks in these floats and are then transferred to their final grow out spot (vertical racks, A Frames, or floats).

The traditional 2" net pots are filled ¾ of perlite and ¼ of potting soil. 1 week old seedlings are then transplanted into these 2" net pots. These 2" net pots containing the seedlings are then placed in seedling trays (44/tray) containing approximately ¼ inch of water. These seedling trays are then placed under the lights in a climate controlled seedling room for two weeks. At three weeks of age these seedlings in the 2" net pots are transferred to the 2' x 4' floats containing 156 holes. They spend 2 weeks in these floats and are then transferred to their final grow out spot (vertical racks, A Frames, or floats).





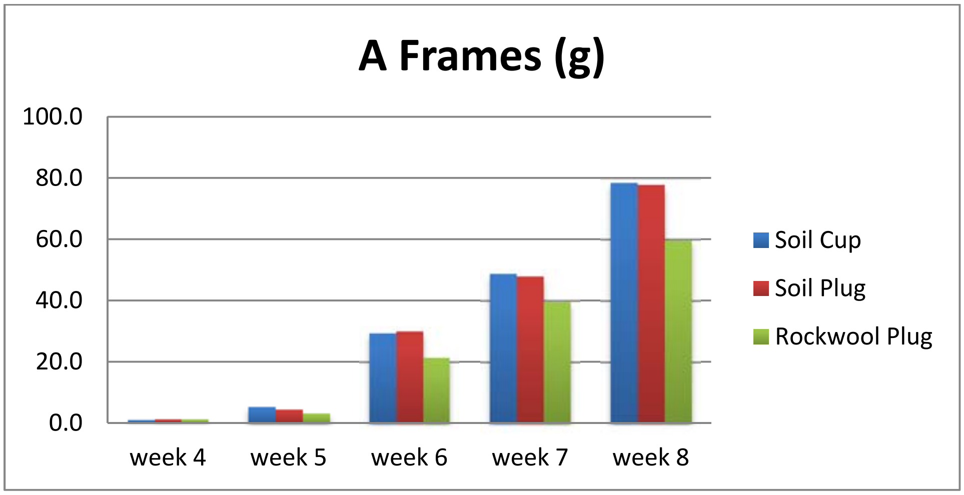


Figure 5. Results of lettuce growth using Rockwool Cube, Soil Plug and Soil Cup approaches in the Floats, Vertical Racks and A Frames. This experiment ran from 3/2/15 – 3/30/15.

The results of these three lettuce growth methods are shown in figure 5. The Rockwool method consistently resulted in poorer plant growth than the two relatively equal soil methods. The same results were also observed using floats, vertical racks or the A Frame approaches. Therefore, we suggest either the soil plug or the 2" soil plus perlite net pot approach. We will continue these experiments, and report further in the next progress update.

In addition to fostering better plant growth, the soil plug approach reduces labor and input costs considerably. Using soil plugs that can be placed directly into our vertical or A Frame Racks eliminates the need for transplanting and cleaning thousands of 2" net pots per week as well as rinsing 2' x 4' floats. This saves nearly 10 hours of labor per week. The soil plugs require only compost and several 200 hole-plug trays. These requirements are far cheaper than purchasing expensive rockwool sheets, and eliminate the need/expense for perlite. Perlite gets in our water system and tends to clog pumps and irrigation lines disrupting the flow of fresh water to the roots of our plants. Given these additional cost/saving advantages the soil plug approach is our current recommendation.

Activity Status as of: 12/31/15

a. *Wicking Bed – Bell Peppers*

A 'wicking bed' was constructed in the greenhouse between troughs two and three. It was made from a wood frame and lined with the same black liner used in the larger hydroponic/aquaponic plant production troughs. The bed consists of an eight-inch layer of sand and gravel with sixteen inches of soil on top. There is a weed mat sandwiched in between the layers to prevent roots from entering the lower layer. Within the bottom layer we have a PVC pipe running the length of the bed. The PVC distributes water from a reservoir evenly throughout the eight-inches of sand and gravel. Flooding the bottom layer allows the water to slowly wick up and into the soil while keeping the first few inches relatively dry, wood chips were added to the soil surface to reduce evaporation.

Aside from the water and nutrient conservation benefits of the wicking bed the technique requires little maintenance by allowing an adequate amount of water to the plants for 5 to 7 days (depending on the cultivar and season). We planted three different Pepper varieties on March 13, 2015. These plants were transplanted into 4" x 4" x 6" pots and placed under High Pressure Sodium grow lights (12 hour photoperiod) in our indoor climate controlled seedling room. They were moved to the wicking bed in the greenhouse on April 1, 2015. The harvest data from a single plant of each variety over the summer of 2015 are reported below.

King of the North (red full bell pepper)
Red - 6/29 – 2 peppers = 0.25 lbs.
Red – 8/1 - 3 peppers = 1 lbs.
Red – 8/5 - 3 peppers = 0.8 lbs.
Red – 8/7 - 1 pepper = 0.25 lbs.
Red – 8/12 - 3 peppers = 0.8 lbs.
Red – 8/21 - 3 peppers = 0.75 lbs.

Golden Cali (yellow full bell pepper)
Green 6/29 – 1 pepper = 0.25 lbs.
Yellow 7/29 – 1 pepper = 0.25 lbs.
Yellow 8/3 – 3 peppers = 0.8 lbs.
Yellow 8/5 – 1 pepper = 0.25 lbs.
Yellow 8/12 – 3 peppers = 0.6 lbs.

Sweet Chocolate (purple/brown medium sized bell)
Ripe – 7/1 – 1 pepper = 0.166 lbs.
Ripe – 7/15 – 3 peppers = 0.5 lbs.
Ripe – 7/24 – 3 peppers = 0.5 lbs.
Ripe – 7/31 – 4 peppers = 0.35 lbs.
Ripe – 8/5 – 5 peppers = 0.4 lbs.
Ripe – 8/12 – 4 peppers = 0.4 lbs.
Ripe – 8/21 – 3 peppers = 0.2 lbs.

Plants were cut back in early September to avoid crowding. The cutting severely slowed yields, and ended the harvesting. In general, we found the Wicking bed was a successful way to cultivate peppers. Wicking bed peppers were more healthy and voluminous when compared to flood/drain and hydroponic techniques. Each plant occupied approximately 2 ft2 of growing space. Our peppers sold for $3/lb. Each variety produced a similar yield averaging roughly .6 lbs/week/plant, or .3lbs/week/ft2. This resulted in a total economic yield from peppers of just under $1.00/week/ft2 or approximately $50.00/ft2/yr. These Peppers did not compete well economically with many of the other produce we have grown in our production system, but the wicking bed method seemed to work well. We are eager to try this method with the more economically attractive Ghost and Hungarian Hot Wax peppers described above.

b. **Sustainability: Aquaponic Floating Raft, Hydropponic Floating Raft and Vertical Hydroponics**

We also compared the input requirements of three different, but comparably scaled, produce production methods. These methods include: Aquaponic floating rafts, hydroponic floating rafts and hydroponic vertical racks. The input requirements examined include: Production space (ft2); Water use (gallons); Electrical use (kwhrs); Natural

Gas use (therms); Propane use (gallons); Gasoline use (gallons) Fish feed (lbs) and Nutrients (lbs). No additional inputs (ie., herbicides, pesticides ect…) are required by these three CEA production methods. We conclude that all of these methods require far less inputs than even the most sustainable of the conventional soil based farming methods, and that hydroponics requires far less inputs than aquaponics.

1. System Design – Aquaponic Floating Rafts

In this approach we use two (16' x 48') plant production troughs filled to a depth of 8" to sustain the production of 800 plants/week. This results in a total of 7,582 gallons of water and requires about 1,800 ft2 of greenhouse floor space. In addition, the fish are kept in nine 2000-gallon tanks filled with 1,800 gallons each for a total of 16,200 gallons. The total volume in the troughs and fish tanks equals 23,782 gallons. The water is pumped from each plant production trough to a natural gas powered heat exchanger to the nine fish tanks and then back to each trough on a continuous 24-hour cycle to maintain a 78 degree F temperature. In addition, an electric air pump aerates each trough and fish tank on a continuous 24-hour cycle. The plants are grown in 2" net pots placed in holes drilled into 1.5" 2' x 4' floating 'rafts' made from rigid polystyrene insulation. The holes are spaced to allow 18 plants per 2' x 4' floating 'raft'.

In addition to the approximately 1800 ft2 of greenhouse growing space required to contain the two aquaponic floating raft production troughs, approximately 2,800 ft2 of interior building space is required for fish tanks (2,000 ft2) seedling growth (60 ft2), washing and processing (240 ft2), cold storage (60 ft2) office work (240 ft2) utilities (120 ft2) and a bathroom (80 ft2).

Over a 12-month period from November '13 to October '14 we tracked the production, space, nutrient, water and energy requirements to operate a simple 800 head per week (two 16' x 48' troughs) approximately 4,600 ft2 aquaponic floating raft production system. Filtered rainwater was added as needed to maintain water levels in our two 1,895-gallon plant production troughs. Tap water was used to wash the produce. The fish are fed according to their density, age and size. This fish feed serves as nutrient for the plants growing on their wastewater. We attempted to maintain TDS levels in the 200-400 ppm range via our feeding rates. Electricity was used to run the water and air pumps, to provide supplemental lighting to the aquaponic floats and the seedlings. Propane fuel was used to maintain a 50 degree F greenhouse air temperature. Natural gas was used to maintain a 68 degrees F building air temperature. No pesticides or herbicides were added, and there was no runoff or soil erosion from our completely closed production system. In fact, we generated significant soil via composting our plant waste over the course of this experiment. Finally, we also tracked gasoline consumption from delivery miles driven to our local customers.

2. System Design – Hydroponic Floating Rafts

In addition to the approximately 1800 ft2 of greenhouse growing space required to contain the hydroponic floating raft production system described above, approximately 800 ft2 of interior building space is required for seedling growth (60 ft2), washing and processing (240 ft2), cold storage (60 ft2) office work (240 ft2) utilities (120 ft2) and a bathroom (80 ft2).

Over a 12-month period from November '14 to October '15 we tracked the production, space, nutrient, water and energy requirements to operate a simple 800 head per week (two 16' x 48' troughs) approximately 2,600 ft2 hydroponic floating raft production system. Filtered rainwater was added as needed to maintain water levels in our two 1,895-gallon plant production troughs. Tap water was used to wash the produce. Hydroponic nutrients were added as needed to maintain TDS levels in the 200-400 ppm range. Electricity was used to run the water and air pumps, to provide supplemental lighting to the hydroponic floats and seedlings. Propane fuel was used to maintain a 45 degree F greenhouse air temperature. Natural gas was used to maintain a 60 degrees F building air temperature. No pesticides or herbicides were added, and there was no runoff or soil erosion from our completely closed production system. In fact, we generated significant soil via composting our plant waste over the course of this experiment. Finally, we tracked gasoline consumption from delivery miles driven to our local customers.

3. System Design – Hydroponic Vertical Racks

In the past two years we have experimented with many 'vertical' approaches. Our most successful (in terms of consistent plant production, sustainability and economic viability) 'vertical' hydroponic production system approach to arise from this experimentation is illustrated in figure 1. In this approach two 8' green treat 2" x 4"'s are joined at the top with a hinge that allows us to adjust the space between the 2” x 4”s at the base. Three of these are used to support the 10’ 2” PVC pipes. ¼” holes are drilled into the three 2” x 4” ‘A Frame’ supports every 3”, and wooden pegs placed in the holes are used two support the 10’ lengths of 2” PVC pipe that run parallel to the floor. Holes (1”) are drilled into these PVC pipes spaced every 6” along their length. Plants are placed into these holes, and their roots are free to dangle in the water running through the pipes. The water is pumped from a 112-gallon nutrient reservoir tank on the floor into a 5-gallon plastic bucket suspended above the ‘A Frame’. The base of the bucket has several barbs that connect to ¼” irrigation tubing which feeds the top PVC pipe in each ‘A Frame’. The water flows by gravity through the eight 10’ lengths of PVC pipe along either side of the ‘A Frame’ and then drains into the nutrient reservoir after exiting the bottom PVC pipe. A Single ‘A Frame’ can support up to 20 10’ 2” PVC pipes with 20 holes per pipe for a total of 400 plants. A set of four ‘A Frames’ allows ample growing time (4 weeks) for a harvest of 400 plants/week from each set.

Figure 1. Photo of our ‘A Frame’ lettuce racks.

In addition to the approximately 500 ft2 of greenhouse growing space to contain the vertical production system described above, approximately 800 ft2 of interior building space is required for seedling growth (60 ft2), washing and processing (240 ft2), cold storage (60 ft2) office work (240 ft2) utilities (120 ft2) and a bathroom (80 ft2).

Over a 6-month period from March ’15 to September ‘15 we tracked the production, space, nutrient, water and energy requirements to operate a simple 800 head per week (2 sets of 4 racks) approximately 1,300 ft2 (500 ft2 greenhouse, 800 ft2 building) vertical hydroponic lettuce production system. Filtered rainwater was added as needed to maintain water levels in our 112-gallon nutrient reservoir. Tap water was used for produce washing. Hydroponic nutrients were added as needed to maintain TDS levels in the 200-400 ppm range. Electric heating was applied to maintain a 60 degree F water temperature, to run the water and air pumps, to provide supplemental lighting to the vertical racks and the seedling lighting. Propane fuel was used to maintain a 50 degree F greenhouse air temperature. Natural gas was used to maintain a 60 degrees F building air temperature. No pesticides or herbicides were added, and there was no runoff or soil erosion from our completely closed production system. In fact, we generated significant soil via composting our plant waste over the course of this experiment. Finally, we tracked gasoline consumption from delivery miles driven to our local customers.

Results:
We monitored the space (ft2), water (gallons), electricity (kwhr), natural gas (therms), propane (gallons), gasoline (gallons), herbicide/pesticide and soil requirements for each of the three CEA methodologies described above. The results of each method are reported below as total annual input requirements, and as input requirements per head of lettuce produced.

1. **Aquaponic floating raft input requirements:**

Land requirements:
Our two 768 ft2 aquaponic floating raft plant production troughs required approximately 1800 ft2 of greenhouse production space. In addition, another 2,800 ft2 of indoor production space was required for the production support activities described for this method above. Total production floor space totaled 4,600 ft2. This system was capable of producing up to 800 heads of lettuce per week, but production of approximately 518 heads/week was the norm. This totaled roughly 26,936 heads per year. Therefore, our hydroponic vertical lettuce production approach required .17 ft2/head.

Water requirements:
Water was lost from our aquaponic floating raft plant production troughs and indoor fish tanks from evaporation, transporation and harvest. In addition, the plant production troughs and fish tanks were filled once initially. These losses varied depending primarily on the greenhouse climate, and proper functioning of our system. Therefore, water was added periodically as needed to our approximately 24,000-gallon production system to compensate for these losses. Over our annual experimental period we added a total of 153,994 gallons. Dividing this annual water usage by our annual lettuce production (26,936 heads) results in an average water requirement of 5.72 gallons per head of lettuce.

Electricity requirements:
The majority of the electrical needs for the aquaponic floating raft production system were for the full-time grow lights in our seedling room, and the seasonal supplemental lighting in our two 768 ft2 plant production troughs. In addition, significant amounts of electricity were needed to run a full-time water pump, drum filter, air pump and seasonal Natural Gas heat pump and a cold-room storage air conditioner. The specific electrical needs for the aquaponic floating raft production system are listed in Table 1.

Equipment	**hours/day**	**watts**	**#**	**kwh/day**
Seedling Rack LED Lighting	12	165	2	3.96
Seedling Rack T8 Lighting	12	32	8	3.07
Grow Lighting (1000 watt HPS)	3	1000	4	12
Grow Lighting (400 watt HPS)	3	400	12	14.4
Grow Lighting (250 watt LED)	3	240	24	17.28
System Water Pump	24	250	1	6
System Air Pump	24	300	1	7.2
System Natural Gas Heat Pump	9	1000	2	18
Drum Filter Pump	3	1000	1	3
Cold Room Storage Air Conditioner	1	920	1	.92

Total (kwhrs/day)	***85.59***
Total (kwhrs/month)	***2567.76***
Total (kwhrs/year)	***30813.12***

Our hydroponic floating raft production system generated approximately 519 heads of lettuce per week or 26,988 heads of lettuce per year, and required a total of 30813.12 kwhrs/year. This results in approximate annual use of 1.14 kwhrs/hd.

Natural Gas:
Natural gas was used to heat approximately 24,000 gallons of water to 78 degrees F, and approximately 2,800 ft2 of interior building space to 70 degrees F. This resulted in a monthly use of 960 therms of Natural Gas, or 11,520 therms annually. Dividing this annual natural gas usage by the approximate annual lettuce production of 26,936 heads results in a natural gas use of .428 therms per head of lettuce.

Propane:
Propane was used to heat the approximately 1800 ft2 of required greenhouse space to 60 degrees F. This resulted in an average monthly use of 220 gallons, or an annual total of 2640 gallons. Dividing this total propane use by the annual production of 26936 heads resulted in a propane use of .098 gallons per head of lettuce.

Gasoline/diesel requirements:
We delivered all lettuce harvested from our aquaponic floating rafts two times per week. All lettuce was delivered from the University of MN, Duluth to the Duluth Whole Foods Co-op (a distance of 10 miles round trip). The delivery vehicle was a Dodge Grand Caravan with an average fuel efficiency of 25 mpg. Therefore, two trips per week consumed .8 gallons of gas per week, or 41.6 gallons per year. Dividing this annual fuel consumption by our annual lettuce production (26,988 heads) results in .01 gallons per head. No diesel fuel was used.

Pesticide and Herbicide requirements:
No pesticides or herbicides were added, and there was no nutrient runoff or soil erosion from our closed production system. In fact, we generated significant soil (see below) by composting the remains of our lettuce plants after harvest.

Soil Erosion:
Victus farms composts all non-consumable lettuce heads and root systems. Our aquaponic floating raft production system generated approximately 3,500 lbs of organic compost from these inputs per year. Dividing this number by our total annual production from this method (26,936 heads) results in .130 lbs soil per head of lettuce.

2. Hydroponic floating raft input requirements:

Land requirements:
Our two 768 ft2 hydroponic floating raft plant production troughs required approximately 1800 ft2 of greenhouse production space. In addition, another 800 ft2 of indoor production space was required for the production support activities described for this method above. Total production floor space totaled 2600 ft2. This system was capable of producing up to 800 heads of lettuce per week, but production of approximately 512 heads/week was the norm. This totaled roughly 26,624 heads per year. Therefore, our hydroponic vertical lettuce production approach required .1 ft2/head.

Water requirements:
Water was lost from our hydroponic floating raft plant production troughs from evaporation, transporation and harvest. In addition, the troughs were filled once initially. These losses varied depending primarily on the greenhouse climate, and proper functioning of our system. Therefore, water was added periodically as needed to our two approximately 1,895 gallon plant production troughs to compensate for these losses. Over our annual experimental period we added a total of 31,469 gallons. Dividing this annual water usage by our annual lettuce production (26,624 heads) results in an average water requirement of 1.18 gallons per head of lettuce.

Electricity requirements:
The majority of the electrical needs for the hydroponic floating raft production system were for the full-time grow lights in our seedling room, and the seasonal supplemental lighting in our two 768 ft2 plant production troughs. In addition, significant amounts of electricity were needed to run a full-time water pump, air pump and seasonal Natural Gas heat pump and a cold-room storage air conditioner. The specific electrical needs for the hydroponic floating raft production system are listed in Table ??.

Equipment	**hours/day**	**watts**	**#**	**kwh/day**
Seedling Rack LED Lighting	12	165	2	3.96
Seedling Rack T8 Lighting	12	32	8	3.07
Grow Lighting (1000 watt HPS)	3	1000	4	12
Grow Lighting (400 watt HPS)	3	400	12	14.4
Grow Lighting (250 watt LED)	3	240	24	17.28
System Water Pump	24	120	2	5.76
System Air Pump	24	150	1	3.6
System Natural Gas Heat Pump	5	1000	2	10
Cold Room Storage Air Conditioner	1	920	1	.92

Total (kwhrs/day)	***70.99***
Total (kwhrs/month)	***2129.76***

Total (kwhrs/year) ***25557.12***

Our hydroponic floating raft production system generated approximately 512 heads of lettuce per week or 26,624 heads of lettuce per year, and required a total of 25,557.12 kwhrs/year. This results in approximate annual use of .96 kwhrs/hd.

Natural Gas:
Natural gas was used to heat approximately 3,800 gallons of water to 62 degrees F, and approximately 800 ft2 of interior building space to 65 degrees F. This resulted in a monthly use of 160 therms of Natural Gas, or 1920 therms annually. Dividing this annual natural gas usage by the approximate annual lettuce production of 26,624 heads results in a natural gas use of .072 therms per head of lettuce.

Propane:
Propane was used to heat the approximately 1800 ft2 of required greenhouse space to 50 degrees F. This resulted in an average monthly use of 165 gallons, or an annual total of 1980 gallons. Dividing this total propane use by the annual production of 26,624 heads resulted in a propane use of .074 gallons per head of lettuce.

Gasoline/diesel requirements:
We delivered all lettuce harvested from our hydroponic floating rafts two times per week. All lettuce was delivered from the University of MN, Duluth to the Duluth Whole Foods Co-op (a distance of 10 miles round trip). The delivery vehicle was a Dodge Grand Caravan with an average fuel efficiency of 25 mpg. Therefore, two trips per week consumed .8 gallons of gas per week, or 41.6 gallons per year. Dividing this annual fuel consumption by our annual lettuce production (17,680 heads) results in .011 gallons per head. No diesel fuel was used.

Pesticide and Herbicide requirements:
No pesticides or herbicides were added, and there was no nutrient runoff or soil erosion from our closed production system. In fact, we generated significant soil (see below) by composting the remains of our lettuce plants after harvest.

Soil Erosion:
Victus farms composts all non-consumable lettuce heads and root systems. Our hydroponic floating raft production system generated approximately 3,600 lbs of organic compost from these inputs per year. Dividing this number by our total annual production from this method (26,624 heads) results in .135 lbs soil per head of lettuce.

3. Hydroponic vertical rack input requirements:

Land requirements:
Our eight vertical ‘A Frame’ lettuce production racks and 120-gallon nutrient reservoir required approximately 500 ft2 of greenhouse production space. In addition, another 800 ft2 of indoor production space was required for the production support activities described above. Total production floor space totaled 1300 ft2. This system was capable of producing up to 800 heads of lettuce per week, but production of approximately 340 heads/week was the norm. This totaled roughly 17,680 heads per year. Therefore, our hydroponic vertical lettuce production approach required only .07 ft2/head.

Water requirements:
Water was lost from our vertical ‘A-Frame’ hydroponic lettuce production system from evaporation, transporation, harvest and leakage. These losses varied depending primarily on the greenhouse climate, and proper functioning of our system. Therefore, water was added periodically as needed to our 112-gallon nutrient reservoir to compensate for these losses. Over our annual experimental period we added a total of 2569 gallons for an average of 6.7 gallons per day. Dividing this annual water usage by our annual lettuce production (17,680 heads) results in an average water requirement of .15 gallons per head of lettuce.

Electricity requirements:
The majority of the electrical needs for the vertical hydroponic racks were for the full-time grow lights in our seedling room, and the seasonal supplemental lighting in our plant production racks. In addition, electricity was

needed to run an intermittent water pump, full-time air pump and seasonal electric water heater and a cold-room storage air conditioner. The specific electrical needs for the vertical rack production system are listed in Table ??.

Equipment	hours/day	watts	#	kwh/day
Seedling Rack LED Lighting	12	165	2	3.96
Seedling Rack T8 Lighting	12	32	8	3.07
Grow Lighting (1000 watt HPS)	3	1000	8	24
Grow Lighting (400 watt HPS)	0	400	6	0
Grow Lighting (250 watt LED)	3	240	8	5.76
System Water Pump	2	240	1	.48
System Air Pump	24	40	1	.96
Electric Wand Heater	4	100	1	.4
Cold Room Storage Air Conditioner	1	920	1	.92

Total (kwhrs/day)	***39.55***
Total (kwhrs/month)	***1186.56***
Total (kwhrs/year)	***14238.72***

Our vertical rack production system generated approximately 340 heads of lettuce per week or 17,680 heads of lettuce per year, and required a total of 14238.72 kwhrs/year. This results in approximate annual use of .81 kwhrs/hd.

Natural Gas:

Natural gas was used to heat approximately 120 gallons of water to 65 degrees F, and approximately 800 ft2 of interior building space to 65 degrees F. This resulted in a monthly use of 90 therms of Natural Gas, or 1080 therms annually. Dividing this annual natural gas usage by the approximate annual lettuce production of 17,680 heads results in a natural gas use of .062 therms per head of lettuce.

Propane:

Propane was used to heat the approximately 500 ft2 of required greenhouse space to 50 degrees F. This resulted in an average monthly use of 60 gallons, or an annual total of 720 gallons. Dividing this total propane use by the annual production of 17,680 heads resulted in a propane use of .041 gallons per head of lettuce.

Gasoline/diesel requirements:

We delivered all lettuce harvested from our racks two times per week. All lettuce was delivered from the University of MN, Duluth to the Duluth Whole Foods Co-op (a distance of 10 miles round trip). The delivery vehicle was a Dodge Grand Caravan with an average fuel efficiency of 25 mpg. Therefore, two trips per week consumed .8 gallons of gas per week, or 41.6 gallons per year. Dividing this annual fuel consumption by our annual lettuce production (17,680 heads) results in .017 gallons per head. No diesel fuel was used.

Pesticide and Herbicide requirements:

No pesticides or herbicides were added, and there was no nutrient runoff or soil erosion from our closed production system. In fact, we generated significant soil (Approximately 5 cubic yards per year) by composting the remains of our lettuce plants after harvest.

Soil Erosion:

Victus farms composts all non-consumable lettuce heads and root systems. Our hydroponic vertical ‘A-frame’ production system generated approximately 2,100 lbs of organic compost from these inputs per year. Dividing this number by our total annual production from this method (17,680 heads) results in .119 lbs soil per head of lettuce.

Each method was scaled for 800 heads per week, but actual weekly production experienced seasonal variation over our annual study. Actual weekly production ranged from a low of approximately 420 heads per week to a high of nearly 730 heads per week. In addition, actual production varied between methods from week to week and throughout the year. Although the floating raft approaches consistently provided greater production than the vertical rack approach these production differences were not large enough to significantly impact input requirements. It was beyond the scope of this study to quantify the impacts of these production fluctuations on input requirements, but they would have had only a minor influence on nutrient and perhaps water requirements. All other inputs were required to maintain optimal parameters for growth regardless of actual production amounts.

The results reported above clearly indicate that the input requirements decreased significantly as we moved from aquaponic to hydroponic production. Hydroponic production requires far less space and water as well as lower water temperatures. Concentrated organic nutrient additions are far cheaper than organic fish feed, and a more efficient way to deliver nutrients to plants. In our experience, the revenues lost from fish sales were more than offset by the input and labor cost savings. These efficiency gains were increased dramatically with the vertical rack method, but plant production was far less consistent. More work is required to improve consistency of these very promising vertical approaches to growth. Finally, all three of the CEA methods detailed above require far less inputs than conventional farming. CEA production methods offer a very promising sustainable alternative to conventional farming.

Final Report Summary:

As discussed in previous reports, we experimented with several different growth methods for many of the species described in the previous section. Given that lettuce was our best potential crop, we summarize the results of the different production methods we examined and end with a detailed analysis of the theoretical and actual economic potential of CEA lettuce production. We produced lettuce using floating rafts and vertical racks both hydroponically and aquaponically. We consistently had our best production results with the ‘deep water’ floating raft approach, and found the addition of fish improved water chemistry and growth rates. Other researchers and entrepreneurs have also noticed that adding fish accelerate plant growth. The mechanism is unclear, but our experience suggests fish increase the concentration of nitrate (NO_3) in the system making Nitrogen far more available to the plants for uptake and growth. In addition, plant roots often release numerous organic acids known to inhibit the growth of competing plants. In a closed hydroponic system such as ours, these organic acids will accumulate in our water until they eventually inhibit plant growth. Somehow, the fish seem to reduce the rate of accumulation of these organic acids. We found it to be far easier to consistently maintain critical water chemistry parameters with the inclusion of fish (even if only in very small concentrations).

We continue to have difficulties achieving consistent plant production in our various Nutrient Film Technique (NFT) ‘vertical rack’ approaches. However, we have experienced periods of promising growth, and continue to experiment with these approaches because of the economic potential they provide (more plants per unit area). Also, in addition to our findings with the deep water floating raft approach, we discovered that aquaponics (the inclusion of fish) seems to provide better water chemistry, hence plant growth for longer periods of time than hydroponics. We found more Nitrate associated with the fish, healthier bacterial assemblages for nutrient regeneration, and less evidence of organic acids inhibiting plant growth. Based on these findings we currently suggest a predominantly hydroponic production system, but with a small population of fish to provide these critical water chemistry benefits.

a. *Potential Production and Revenues:*

Given our results over the past two years, and the fact that lettuce was our best potential economic crop, we provide the following economic summary and projections based on CEA lettuce production at Victus Farms.

The total potential production of lettuce with our ‘floating raft’ approach was 800 plants per week at 4 ounces per plant for a total of 3,200 ounces or 200 lbs. If all lettuce production can be sold as 5 ounce clams for $2.65/each that totals $8,736/month. Figures 1-9 compare our actual lettuce production yields with total potential yields. Total lettuce production and sales over the past 2.5 years at Victus Farms fluctuated dramatically (Figures 1-9) due to several factors described below. In 2014 our plants were grown aquaponically until we experienced a large fish kill (bacterial infection) in October of 2014. In 2015 our plants were grown predominantly hydroponically. In 2016 we grew our plants hydroponically, but with a small population of fish included. We experienced low production rates in 2016 due to a root rot (pythium) infection that we were slow to diagnose and ultimately treat. Finally, we ramped down production in the spring of 2016 as part of our exit from the facility associated with it sale to Mariner Farms.

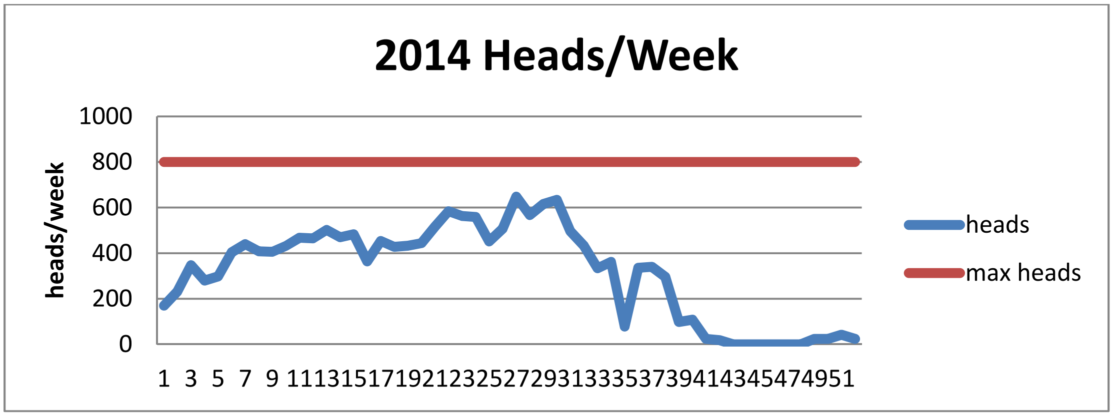


Figure 1. Total lettuce production in 2014. Week #1 is January 1st. Week #52 is December 31st. The red line is the number of heads planted each week.

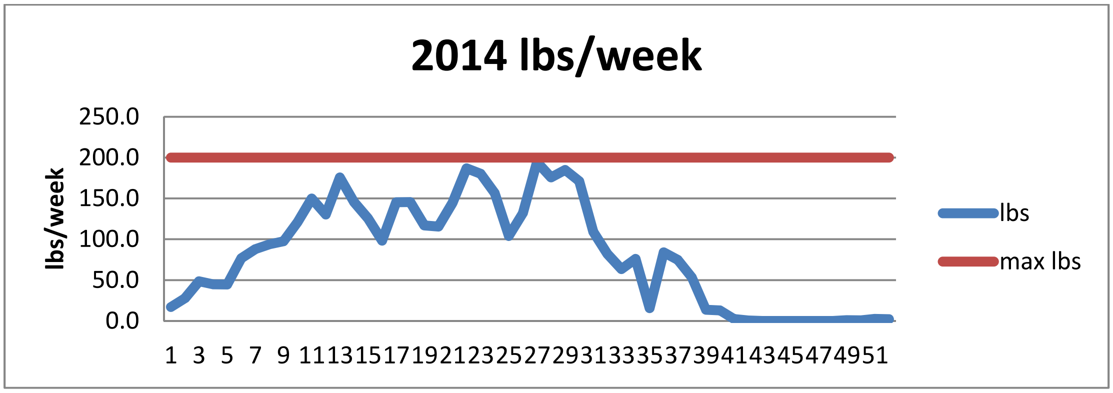


Figure 2. The total lettuce harvest in lbs/week in 2014. Week #1 is January 1st. Week #52 is December 31st. The red line is the maximum number of lbs/week assuming an average head size of .25 pounds (4 ounces).

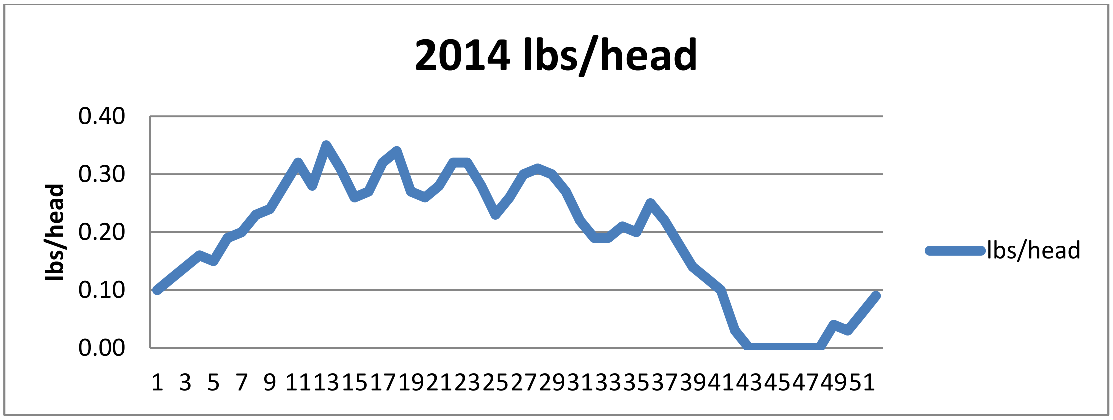


Figure 3. The average size of an individual head of lettuce harvested each week in lbs/head in 2014. Week #1 is January 1st. Week #52 is December 31st.

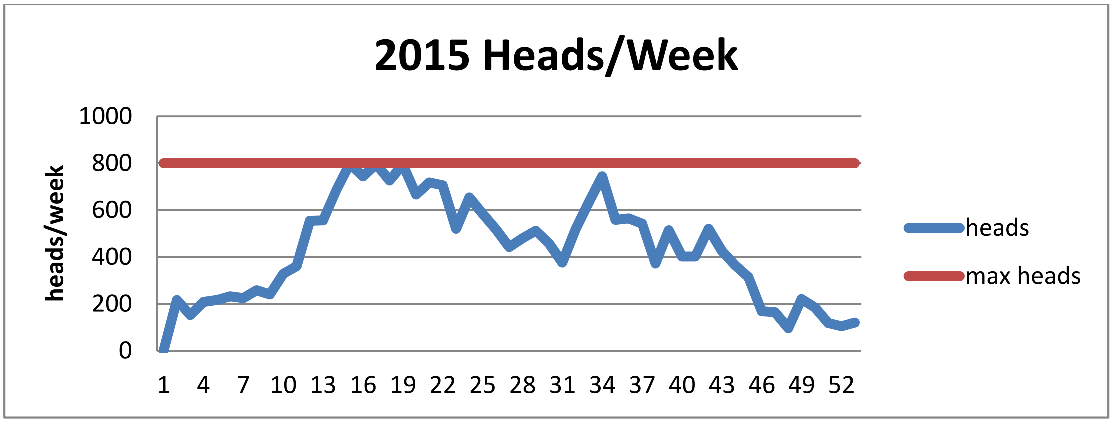


Figure 4. Total lettuce production in 2015. Week #1 is January 1st. Week #52 is December 31st. The red line is the number of heads planted each week.

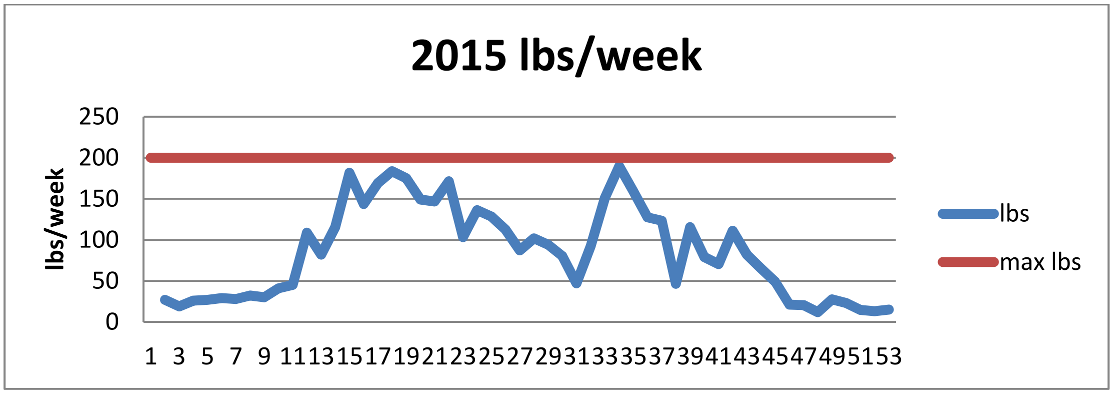


Figure 5. The total lettuce harvest in lbs/week in 2015. Week #1 is January 1st. Week #52 is December 31st. The red line is the maximum number of lbs/week assuming an average head size of .25 pounds (4 ounces).

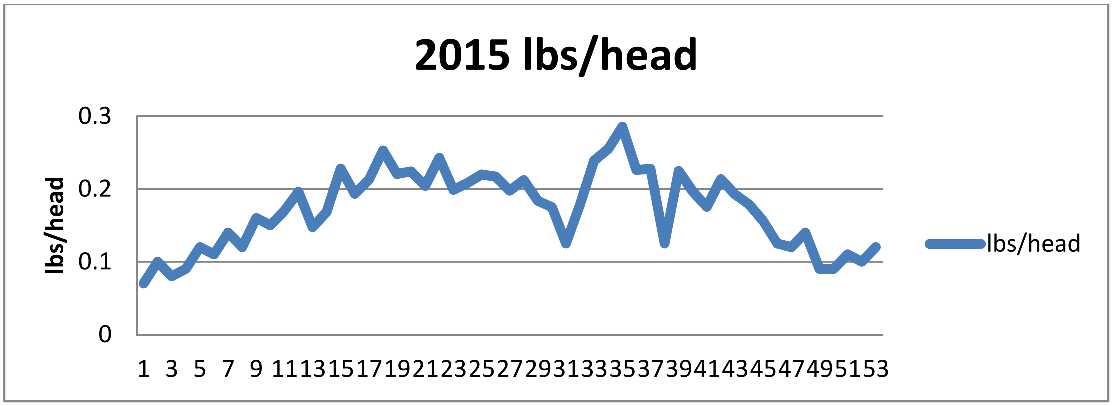


Figure 6. The average size of an individual head of lettuce harvested each week in lbs/head in 2015. Week #1 is January 1st. Week #52 is December 31st.

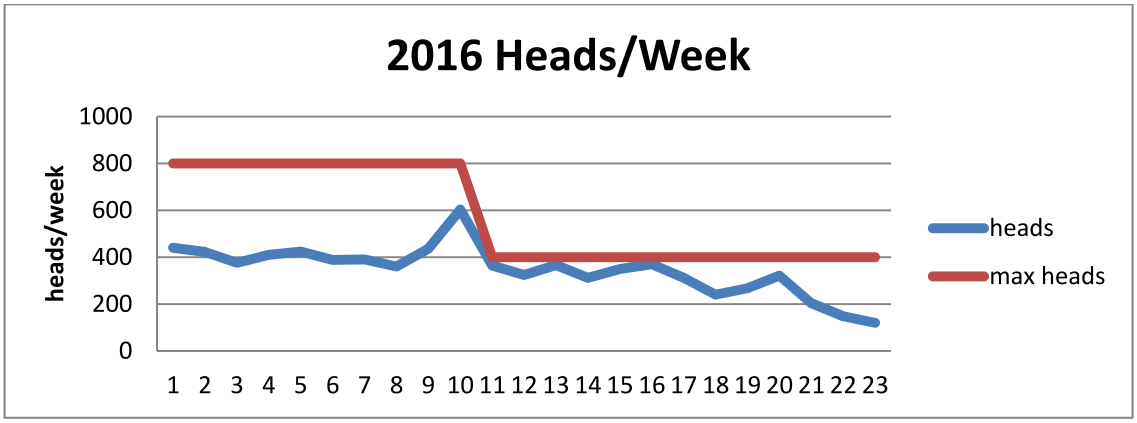


Figure 7. Total lettuce production in 2016. Week #1 is January 1st. Week #23 is June 6th. The red line is the number of heads planted each week.

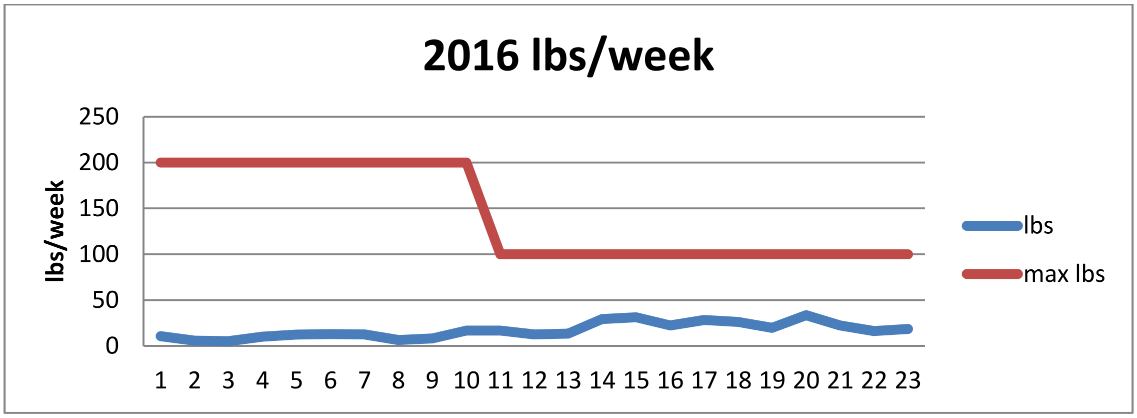


Figure 8. The total lettuce harvest in lbs/week in 2016. Week #1 is January 1st. Week #23 is June 6th. The red line is the maximum number of lbs/week assuming an average head size of .25 pounds (4 ounces).

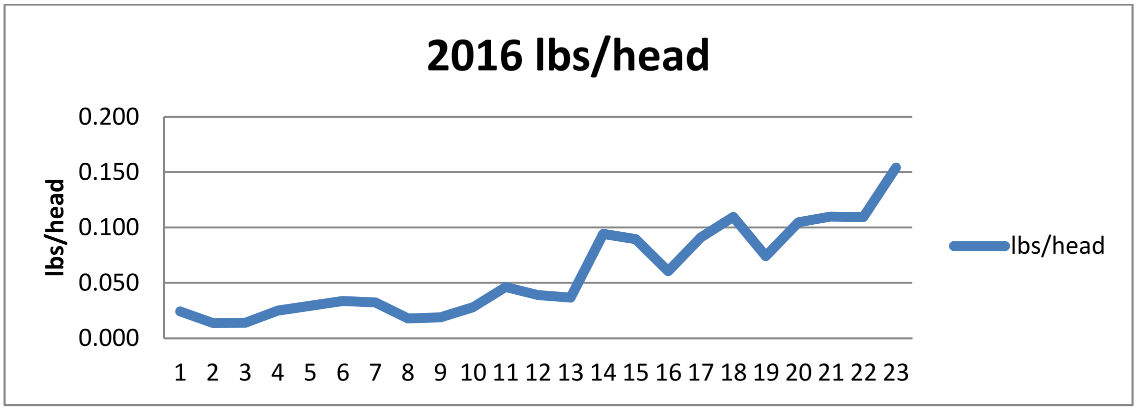


Figure 9. The average size of an individual head of lettuce harvested each week in lbs/head in 2016. Week #1 is January 1st. Week #23 is June 6th.

b. Reasons for Production and Revenue Shortfalls:

If we begin by planting 800 plants/week the first source of mortality is the germination rate. We, and others, have found that the germination rate depends on seed quality, temperature, humidity, proper seedling watering, nutrient and soil type. Our germination rates varied from approximately 30% to nearly 100%, and we were consistently able to achieve germination rates above 80%. Planting more than 800 plants/week is the best way to guard against germination failure, but can add significantly to operational costs.

Our seedlings were transplanted into 2" net pots and then placed in production troughs for 6 weeks. In this growth period, we experienced mortality rates that varied from 5-100%, but we were able to consistently achieve mortality rates of less than 20%. The critical factors influencing these mortality rates included water chemistry parameters (temperature, oxygen, pH, nutrient concentration, nutrient availability, organic acid concentration, and the health of ourn microbial population) as well as external plant environmental factors such as temperature, humidity and light. The most difficult aspect of CEA is consistently maintaining these parameters in the plants narrow tolerance ranges. Healthy plants are incredibly resistant to pests, but if the plants become stressed in any way, pests will take their toll (predominantly Aphids and root rot fungal infections). We have found CEA to be both a science and an art. Practitioners clearly get better with experience. This was certainly our experience.

Finally, as any good farmer knows, it is difficult to match these variable production yields with variable consumer demand. We had several grocery store and restaurant customers who purchased variable lettuce quantities from week to week. We sold our lettuce by the head (approximately $3/lb), by the pound ($4.50/lb) and in 5-ounce clamshells ($10.60/lb). Clearly, it would have been most profitable to sell all our lettuce in 5-ounce clamshells, but this was not always possible given fluctuating consumer demand for these lettuce products.

Given all theses interacting parameters controlling our production yields we consistently fell short of our maximum potential production target of 800 plants/week, and our maximum potential monthly sales revenues ($8,736/month). The production data illustrated above generated an average of approximately $4,000/month in lettuce sales in the good summer months, and about $1,000/month in the poor winter months. However, as our methods improved we were able to more consistently approach these production and sales goals. Perhaps more importantly, we were also able to squeeze 800/plants per week into a smaller space by decreasing the required space between plants and by reducing our growth period from 10 to 7 weeks by increasing plant health and growth rates via a better understanding and more consistent control of the water chemistry parameters described above. We are now at a point where our maximum potential yields at Victus Farms are 800 plants/week per trough, and (with four production troughs) our corresponding potential revenues are $34,944/month.

c. Operational Costs:

Our operational costs consisted of labor, utilities, insurance/certifications and supplies. Victus Farms was simultaneously running a model business to determine economic viability and conducting research/educational activities. We also enjoyed a degree of university subsidized student labor. Finally, these costs varied seasonally and over the duration of the project. These factors make it difficult to accurately determine monthly operational costs at Victus Farms for comparison to above revenues. Below we describe total monthly operational costs and attempt to adjust that number to account for the factors described above and arrive at an estimate to inform economic viability for a model business operation.

Table 1. Estimated average total monthly costs at Victus Farms, a 6,000 ft2 greenhouse CEA research/educational/proof of concept facility generating $2,000 - $5,000/month in sales revenues.

Dr. Mageau (project director)	$500
Manager (.74 FTE project manager)	$3,600
Assistant Manager (.6 FTE assistant manager)	$2,100
UMD student (.5 FTE)	$200
UMD student (.5 FTE)	$200
UMD student (.5 FTE)	$200
Travel (Duluth to Silver Bay, MN)	$700
Supplies and equipment	$1,500
Electric	$500
Natural Gas	$600
Water	$100
Propane	$300
Total	***$10,400***

The actual costs of running a small CEA production business can be estimated from the above Victus Farms project costs. Eliminating research and educational expenses reduce the required costs, but the dramatic increase in production and sales (from approx. $4,000/month to $30,000/month) will drive up supply/equipment costs (ie., nutrient, soil, seeds, plastic clamshells, labels etc…). The required labor can be reduced to two .5 FTE managers with experience in growth/production, marketing and distribution as well as three .5 FTE workers with basic knowledge in CEA production. The travel costs from University of MN, Duluth to Silver Bay, MN (100 mile round trip – approx. 4 days/week) can be replaced by a simple distribution/delivery cost. The supplies and equipment costs can be reduced by approx. 50% with the elimination of research and education expenses, but then increased by a factor of roughly 10 to account for roughly ten fold increase in production and sales. Insurance, capital and organic certification costs are added. Utility costs can be reduced with the elimination of research expenses, but then increased slightly to account for larger production.

Table #2. Estimated monthly operational costs for a 6,000 ft2 greenhouse CEA business generating $30,000 - $35,000/month in sales revenues.

Manager (.5 FTE)	$2,500
Assistant Manager (.5 FTE)	$2,000
Part time staff (.5 FTE @ $12/hr)	$1000
Part time staff (.5 FTE @ $12/hr)	$1000
Part time staff (.5 FTE @ $12/hr)	$1000
Distribution (leased delivery vehicle)	$500
Supplies and equipment	$8000
Insurance	$150
Organic Certification	$150
Capital financing	$2,500
Electric	$600
Natural Gas	$700
Water	$100
Propane	$300
Total	***$20,500***

d. Economic Viability

The analysis above suggests economic viability is possible given a team that includes skilled growers and marketing experts to consistently sell product. Theoretically, with current methods in 6,000 ft2 of greenhouse space, one can expect revenues up to $35,000/month with monthly operational costs of approximately $20,000. This leaves approximately $10,000 - $15,000/month in profit. In practice, we have yet to achieve these numbers, but feel extremely confident that it can be done.

In fact, the Victus Farms facility has recently been sold to Mariner Farms, a private local business. We are awaiting the official close of the sale as we write this final report. In less than five years we have put this concept into practice, proven its potential economic viability and turned over the facility to a private business. In addition, several members of the Victus Farms team have recently built a small greenhouse in Duluth, MN and started a new small CEA production business. We hope to gradually grow this operation as revenues and new customers allow. We expect other businesses to follow in our region of Minnesota and beyond. In the last 10 years, interest in controlled environmental agriculture (CEA) has flourished. We were fortunate to contribute to these exciting developments in sustainable agriculture. A wide variety of production methods have been developed, and many new businesses have emerged. We hope our project will provide a local model for CEA production and serve as a catalyst to launch many environmentally sustainable and economically successful food production/distribution businesses in Minnesota and beyond.

V. DISSEMINATION:

Description: Dissemination of project results will occur via a wide variety of methods. Project activities have and will continue to be widely reported in the regional media (TV, Newspaper, Radio etc…). Results will also be included in numerous presentations and tours to be scheduled over the next two years. Project results will be added to our project website (www.victusfarms.org). Finally, project results will be described in final reporting, journal publications and possibly a book on the subject.

Status as of: 12/31/14

Presentations

Mageau, M.T., November 20th, 2014. The Future of Food. UMD's CLA Geography Awareness Week. Duluth, MN.
Mageau, M.T., November 25th, 2014. Victus Farms. Natural Resources Research Institute Seminar. Duluth, MN.
Mageau, M.T., December 1st, 2014. Victus Farms Update. Clean Energy Research Teams Steering Committee Meeting. Duluth, MN.

Victus Farms Tours:

7/1/14. Wolf Ridge Environmental Learning Center
7/3/14. US Senator Amy Klobuchar
7/24/14. Iron Range Resources Rehabilitation Board (IRRRB)Commissioner Tony Sertich.

10/29/14. Superior High School Science Teachers
11/10/14. Jennifer Madole's Duluth East High School Plant Science Class
11/19/14. Leah Bott's Silver Bay Middle School Class
12/8/14. Michael Hoops and Delegation from Central Lakes College out of Brainerd, MN.

Media Coverage:
7/4/14. Senator Klobuchar Visits Sustainable Farm in Silver Bay, MN. KBJR TV 6 Northlands News Center. www.northlandsnewscenter.com
9/10/14. How to Grow Lettuce and Fish Indoors, All Year Long. National Public Radio's Marketplace. By Chris Julin. www.marketplace.org.

Publications and Technical Reports:
Mageau M.T. 10/16/14. IRRRB Technical Report. Victus Farms Economic Update.
Mageau M.T. 10/18/14. The Aquaponics Solution. In Review. Solutions Journal. www.thesolutionsjournal.com.

Status as of: 6/30/15
Presentations
Mageau, M.T., February 7th, 2015. The Future of Farming. Duluth Whole Foods Co-op Spring Fest. Duluth, MN.
Mageau, M.T., March 14th, 2015. Victus Farms. University of MN's Learning Life Program. St Paul, MN
Mageau, M.T., May 18th, 2015. Victus Farms Update. Will Steger Climate Change Meeting. Duluth, MN
Mageau, M.T., June 1st, 2015. Victus Farms Update. Board Meeting of the NE Region Sustainable Development Program. Duluth, MN

Victus Farms Tours:
1/30/15 Tony Mancuso, St. Louis County Property Manager and several St. Louis County Commissioners
2/18/15. Paul Christensen, MN Department of Human Services, Director, Moose Lake Correctional Facility
2/25/15. Josthna Harris. Will Steger Foundation
4/13/15. Michael Kaarsch, Produce Director, and several staff, Duluth Whole Foods Co-op
5/8/15. Michael Hoops and Delegation from Central Lakes College out of Brainerd, MN.
5/29/15. Jennifer Madole's Duluth East High School Plant Science Class
6/3/15. Michele Scherman RN, MS, Dr. Nick Phelps and a group of water research scientists from Maylasia and the Phillipenes University of MN's, Bioproducts and Biosystems Engineering Department
6/15/15. Hunt Utilities Group, Brainerd, MN
6/17/15. Normana Township Gardeners Club

Media Coverage:
2/3/15. Lisa Kazcke. Company Plans Aquaponic Farm for Silver Bay and International Falls. Duluth News Tribune.
2/10/15. How to Grow Lettuce and Fish Indoors, All Year Long. National Public Radio's Marketplace. By Chris Julin. www.marketplace.org.
3/4/15. Lettuce Be: University of MN College of Continuing Education Newsletter. http://cce.umn.edu/news/aquaponics-course.
6/20/15. My Green Life. KBJR TV 6 Northlands News Center. www.northlandsnewscenter.com

Publications and Technical Reports:
Mageau, M.T., 4/17/15. Integrated Fish, Plant and Algal Production System: Community Outreach. UMD Strategic Plan Initiative: Community Partnership Grants. University of MN, Duluth.

Mageau M.T., et al., 6/1/15. Greenhouse Production Systems for two Remote Communities. For Confederation College: Thunder Bay, Ontario, Canada.

Mageau M.T., et al., 6/23/15. The Aquaponics Solution. May-June. pp 51-59. Solutions Journal. www.thesolutionsjournal.com.

Status as of: 12/31/15
Presentations
Mageau, M.T., September 2nd, 2015. The Future of Farming. St Louis County Master Gardeners. Duluth, MN.
Mageau, M.T., November 10th, 2015. Victus Farms. UMD Sustainability Fair, UMD.

Mageau, M.T., December 11th, 2015. Victus Farms . Central Lakes College's Controlled Environmental Agriculture Conference. Brainerd, MN

Victus Farms Tours:
7/20/15 Minnesota Sea Grant, Program Officers and Environmental Educators from UMD
8/3/15 Economic Writer, MN Star and Tribune
8/5/15 Wolf Ridge Environmental Learning Center, Executive Directors and Staff Members
10/23/15 Lowell Urban, MN Department of Agriculture
11/4/15 David Chasson, Pinehab Rehabilitation Center

Media Coverage:
Nick Wall and Mike Mageau, Exploring the Potential for Northern Aquaponics at Victus Farms. December 2015. MN Sea Grant's Seiche Newsletter.

Publications and Technical Reports:
Mageau, M.T., 8/1/15. Victus Farms: Integrated Fish, Plant and Algal Production System. U of MN's Healthy Foods Healthy Lives Initiative. Final Technical Report for $25,000 1-year project February 2014-February 2015.

Mageau, M.T. 9/12/15. Victus Farms: Comparing Hydroponic and Aquaponic Plant Production. U of MN's Grant and Aid Program. Final Technical Report for $34,000 1-year project January 2014 - January 2015.

Mageau, M.T. 7/12/15. Victus Farms: Biodiesel from Algae. University of MN's Northeast Region Sustainable Development Partnership Agreement (NMSDP). Final Report for $6,000 1-year project (May 2014 – June 2015.

Mageau, M.T. 11/12/15. Sustainable Development Research Opportunities Program (SDROP). University of MN's Northeast Region Sustainable Development Partnership Agreement (NMSDP). Final Report for $6,000 1-year project January 2014 – January 2015.

Final Report Summary:
Since our last semi-annual report (12/31/2015) we have added three presentations, two publications and several additional tours to our list of dissemination activities.

2016 Presentations:
Mageau, M.T. January 19-21, 2016. Environmental Sustainability and Economic Viability of CEA. 16th National Conference and Global Forum on Science, Policy and the Environment: The Food-Energy-Water Nexus. Washington, D.C.

Mageau, M.T., February 26th, 2016. Victus Farms: Environmental Sustainability and Economic Viability. Central Lakes College's Advanced Indoor Food Production Workshop. Brainerd, MN

Mageau, M.T., May 3rd, 2016. Victus Farms: Environmental Sustainability and Economic Viability. Aquaponics in Minnesota: Recent Findings in Economic Sustainability. University of MN. St. Paul, MN.

Publications:
Mageau, M.T., Baylor Radtke, Jake Fazendin, Anna Lee and Tony Ledin. July 2016. Environmental Sustainability of CEA. Journal Ecological Economics. In Review.

Mageau, M.T., Baylor Radtke, Jake Fazendin, Anna Lee and Tony Ledin. July 2016. Economic Viability of CEA. Journal of Ecological Economics. In Prep.

Since the LCCMR funded portion of our project began in June of 2014 we have conducted numerous dissemination activities. These include local, national and global presentations (13 total); Tours of the Victus Farms facility to a wide variety of groups/individuals (over 20 in total); Publications and Technical Reports (12 total) and numerous media stories (8 total) in local newspapers, TV stations, Radio Stations and University of MN, communication outlets. Therefore, we have been fortunate to enjoy a great deal of interest in our work at Victus Farms over the past several years, and have had numerous opportunities to communicate our work to a broad audience from local hobbyists to community groups to private businesses to university researchers, to prominent, local, state and national policy makers.

VI. PROJECT BUDGET SUMMARY:

A. ENRTF Budget Overview:

Budget Category	$ Amount	Explanation
UMD Contract:		
Dr Mageau: UMD Assistant Professor -- .2 FTE	$19,000	Coordinating all project work
Baylor Radtke: UMD Senior Research Assistant -- 1.4 FTE	$60,000	Conducting project work
UMD Research Assistant: 1 FTE	$31,000	Conducting project work
UMD Undergraduate Students: 1.2 FTE	$24,000	Conducting project work
Total Salaries	***$134,000***	
Equipment, Tools and Supplies:		
Fish Feed	$9,000	Fuels all biological growth in production system
PVC Piping and Supports	$5,500	For vertical and horizontal column construction
Water pumps:	$3,500	Delivering water to columns and new trough
Hanging Materials:	$2,000	For suspending PVC columns from rafters
Tools: (Table Saw, Drill etc…)	$2,000	For all project construction
Seeds, Spores, Seedlings, animal cultures	$3,000	For all new species innocula
Total Equip, Tools and Supplies	***$25,000***	
Printing:	$1,000	Data sheets, flyers, brochures, posters
Travel: UMD mileage	$16,000	Daily Transport from Duluth (UMD) to Silver Bay
Total UMD Contract	**$176,000**	
TOTAL ENRTF BUDGET:	**$176,000**	

Explanation of Use of Classified Staff: N/A

Explanation of Capital Expenditures Greater Than $5,000: N/A

Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: N/A

Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation: 3.8 FTE

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
Non-state			
U of MN Grant and Aid	$32,000	$0	Salary, equipment and supplies
U of MN Duluth Start-up funds	$12,000	$0	Salary, equipment and supplies
State	$	$	
TOTAL OTHER FUNDS:	**$**	**$**	

VII. PROJECT STRATEGY:

A. Project Partners:

Lana Fralich, City Administrator, Silver Bay, MN will oversee project and reporting. Dr. Mageau, UMD Assistant Professor, and Baylor Radtke, UMD Researcher, will coordinate work with new species introductions and production system design changes for innovative new growth methodologies. Research assistants and students from UMD will help with all proposed activities as directed.

B. Project Impact and Long-term Strategy:

The City of Silver Bay has taken a non-conventional approach to economic development by being the developer. Typical municipalities wait for a business to come into their community, Silver Bay is creating the businesses that can co-locate within our 110 acre Eco-Industrial Park. In today's tough economy, businesses are not willing to invest in the time and costs involved in proving a concept. If the public takes the role in this early project development, the private sector is more likely to invest in actual business thus forming a positive public-private partnership. However, by taking on the role as the developer it is important for our City to align itself with researchers, educators, and financial partners to help prove the concepts identified in order to entice the private investor. The long-term strategy is to build out the park, expand Victus Farms throughout the state, and secure the University educational system as the leader in this innovative project development. Each of the project activities identified in this proposal is an extension of the initial proven concept of a closed loop system using renewable energy sources and creating food and fuel for local consumption. Future funding needs will be important to continue fostering new ways to improve efficiencies, creating new concepts, and enhancing student and workforce development especially during these start up years. We expect that as the private sector expands these proven concepts, they will invest in research and development funds to the University in exchange for the knowledge obtained. This provides the private sector current University findings at an annual fixed cost.

C. Spending History:

Funding Source	M.L. 2008 or FY09	M.L. 2009 or FY10	M.L. 2010 or FY11	M.L. 2011 or FY12-13	M.L. 2013 or FY14
DEED				$579,975	
IRRRB				$300,000	
Legislature – Taconite Tax				$299,975	
Lake County				$50,000	
City of Silver Bay – in kind				$87,310	
UMD – CLA				$26,000	
U OF MN – NMSDP				$10,000	
UMD – Strategic Initiative				$3,000	
City of Silver Bay - cash				$105,000	

VIII. ACQUISITION/RESTORATION LIST: N/A

IX. VISUAL ELEMENT or MAP(S): Block 4, Lot 1 is location of Victus Farms.

X. ACQUISITION/RESTORATION REQUIREMENTS WORKSHEET: N/A

XI. RESEARCH ADDENDUM: N/A

XII. REPORTING REQUIREMENTS:

Periodic work plan status update reports will be submitted no later than 12/31/14, 6/30/15, and 12/31/15. A final report and associated products will be submitted between June 30 and August 15, 2016.

Environment and Natural Resources Trust Fund
M.L. 2014 Project Budget

Project Title: Expansion of Greenhouse Production
Legal Citation: M.L. 2014, Chp. 226, Sec. 2, Subd. 06k
Project Manager: Lana Fralich
Organization: City of Silver Bay, MN
M.L. 2014 ENRTF Appropriation: $ *176,000*
Project Length and Completion Date: 2 Years, June 30th, 2016
Date of Report: Dec *30th, 2015*

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	**Activity 1 Budget**	**Amount Spent**	**Activity 1 Balance**	**Activity 2 Budget**	**Amount Spent**	**Activity 2 Balance**	**TOTAL BUDGET**	**TOTAL BALANCE**
BUDGET ITEM	***Introducing new animals and plants***			***Exploring new growth methods***				
UMD Contract:								
Dr. Michael T. Mageau - UMD Assistant Professor - 10% FTE plus 44% fringe per year	$7,500	$7,500	$0	$11,500	$11,500	$0	$19,000	$0
Baylor Radtke - UMD Senior Research Assistant - 70% FTE plus 14% fringe per year	$21,000	$21,000	$0	$39,000	$39,000	$0	$60,000	$0
UMD Research Assistant - 50% FTE plus 14% fringe per year	$10,500	$10,500	$0	$20,500	$20,500	$0	$31,000	$0
UMD Undergraduate Students - 2,400 hrs @ $10/hr	$10,000	$10,000	$0	$14,000	$14,000	$0	$24,000	$0
Equipment, Tools, Supplies								
Fish Feed (9,000 lbs @ $1/lb)	$3,500	$3,500	$0	$5,500	$5,500	$0	$9,000	$0
PVC Piping and supports -- for construction of vertical and horizontal columns	$1,000	$1,000	$0	$4,500	$4,500	$0	$5,500	$0
Water Pumps -- for new trough design flows, and feeding water to new vertical/horizontal columns	$1,500	$1,500	$0	$2,000	$2,000	$0	$3,500	$0
Hanging materials -- ropes/chains, clips and fasteners for suspending PVC vertical and horizontal columns from the greenhouse rafters				$2,000	$2,000	$0	$2,000	$0
Misc tools - table saw, drill, drill bits etc..	$1,000	$1,000	$0	$1,000	$1,000	$0	$2,000	$0
Seeds, spores, seedlings	$2,500	$2,500	$0	$500	$500	$0	$3,000	$0
Printing: Data Sheets, flyers, brochures, posters *(List types of printing costs anticipated.)*	$500	$500	$0	$500	$500	$0	$1,000	$0
Travel expenses in Minnesota: Dialy Transport from Duluth (UMD) to Silver Bay	$7,000	$7,000	$0	$9,000	$9,000	$0	$16,000	$0
COLUMN TOTAL	**$66,000**	**$66,000**	**$0**	**$110,000**	**$110,000**	**$0**	**$176,000**	**$0**

Title: The Aquaponics Solution

Please see for official journal version:
http://www.thesolutionsjournal.com/node/237355

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I. Acknowledgements

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II. Abstract/Author Summary

Our current industrial food system is unsustainable. Demand for food continues to grow while soil erosion, groundwater depletion and climate change are constricting supply. In addition, intensive use of synthetic fertilizers, pesticides, water, fossil fuels and genetic engineering are eroding human, community and environmental health. The rise of local, sustainable food systems present solutions to many of these problems, but these approaches are unable to consistently provide quality food on an annual basis. Aquaponics holds the promise of solving this fundamental local food system's problem, and does so while requiring far less land, water, fertilizers, pesticides, fossil fuels and genetic engineering. We report on a novel, sustainable and economically viable model for aquaponic food production year-round in a harsh winter climate.

III. Key Concepts

- Our current industrial food system is environmentally and socially unsustainable
- The rise of local, sustainable food systems present solutions to many of these environmental and social problems, but most are unable to provide consistent supply on an annual basis
- Aquaponics holds the promise of solving this fundamental annual supply problem while requiring far less land, water, energy, fertilizer, pesticide and herbicide inputs than any type of conventional farming
- Victus Farms is a large (9,000 ft2) aquaponic facility designed to serve as a research, educational and proof of concept system. It has been operational for over two years, and has served the above goals very well
- Wicked Fin Aquatic Farms has emerged from the lessons learned with Victus Farms. It was designed to serve as a small, inexpensive, efficient and economically viable model of aquaponic production to be duplicated around the world in an effort to strengthen local and sustainable food systems. This replication has already begun.

Problems with Industrial Food Systems

Global food production is having a hard time keeping up with demand, and trends suggest things are only going to get more difficult (1). Global demand for food is growing as human and grazing animal populations increase, more people are changing their diets to include more meat, and more crops are used for biofuel production. On the other hand, it is getting more difficult to continuously increase annual agricultural yields as the downward pressure of soil erosion/degradation, aquifer depletion and irrigation water supply complications due to melting glaciers begins to outpace technological advances in agricultural production (1). We are encountering many problems as we try to meet these challenging trends by squeezing ever more production from our remaining agricultural land.

The majority of our food and animal feed now comes from large-scale industrial crop production using a Mono-cropping approach. This involves growing a single crop over a large area of land. This method became widespread in most industrialized countries in the 1940's and 1950's at the expense of the small family farm as farming became more commodity and less subsistence based. This approach increases mechanization, and demands the use of fossil fuels, fertilizers, pesticides, herbicides, irrigation water and genetic engineering. All of these factors decrease the need for human labor, and ultimately reduce crop prices. While proponents of industrial agriculture claim to have modernized and streamlined the production of food in the United States, such evolution has been at the expense of environmental, human and community health (2).

Industrial farming practices have generated numerous environmental impacts including soil erosion and degradation, water pollution, air pollution and biodiversity loss. These environmental impacts have led to numerous human health problems including ingestion of cancer causing pesticides, herbicides and hormones, increased allergens and anti-biotic resistant bacteria, infectious disease incubation and dispersal and a wide range of respiratory problems from exposure to air pollutants (particulates, Hydrogen Sulfide, Ammonia). Finally, Industrial farms typically import most necessary inputs and export most products leading to local economic stagnation. Surrounding property values also decline significantly as the result of odor, pollution and their associated human health problems. When these local economies degrade their community infrastructure (schools, parks etc…) soon deteriorates as well. In this vicious cycle, environmental and human health problems work together to degrade the communities surrounding these large-scale farming operations (2).

More sustainable food production techniques offer many solutions to the problems with industrial farming outlined above, but have difficulty generating reliable, adequate production (amount and variety) for a given region over the course of an entire calendar year. This is where the aquaponic solution enters the equation. Aquaponics offers the potential to reliably generate large quantities and varieties of food from very small urban spaces in any season. If aquaponic food production methods can be made environmentally sustainable and economically viable, this approach could be used in combination with more typical sustainable farming methods to bring us far closer to a more competitive local food system. There are currently many groups in the Midwestern US attempting to do just that (3), and we believe we have developed a sustainable and economically viable solution.

Aquaponics

Aquaponics refers to the combined production of fish and plants in what is commonly referred to recirculating aquaculture (4). Nutrient rich waste-water from fish supports plant growth, and the plants clean the water so that it can be safely returned to the fish. The concept has grown increasingly popular in the last few decades, and aquaponics is now regarded by many as the future of food production. It holds the promise of becoming an economically viable way to consistently grow sustainable, local, organic food.

Modern aquaponics dates back to early work at the New Alchemy Institute and three key university projects. The first physical project undertaken by the New Alchemy Institute was a geodesic dome greenhouse that contained fish and plants growing synergistically. William McLarney published a series of articles and ultimately a book documenting this pioneering work from 1974-1984 (5,6,7,8). Mark McMurtry and Doug Sanders from North Carolina State University began their aquaponics system in the mid-1980's. Their system contained tilapia along with tomatoes and cucumbers growing in a sandy medium which doubles as a reciprocating bio-filter. They have used this system to demonstrate sand culturing of plants on fish waste-water (9), water use efficiency (10) and the economic improvements of combined fish and plant operations versus either in isolation (11). Also in the mid-1980's, Dr. James Rakocy developed a modified aquaponic system at the University of the Virgin Islands. Dr. Rakocy added rotating mechanical bio-filters between the fish tanks and the plant growth troughs to replace the sand medium, and developed the first 'raft' aquaponic system. Dr. Rakocy has made numerous contributions (Fish feed, key scaling metrics, nutrient dynamics, pest/disease control, solids removal and bio-filtration) to auquaponic knowledge over the past two decades (12,13,14). Dr. Nick Savidov, at the University of Alberta's Crop Diversification Center in Brooks Alberta, started an aquaponic system in the mid 1990's modeled after Dr. Rakocy's, but modified for cold-climate applications. Savidov developed a method for recycling all solids in-situ eliminating the difficulties of sediment removal and disposal, and regenerating more internal nutrient to support plant growth. Savidov also demonstrated that plants grew better on fish waste-water than conventional hydroponic nutrient solutions, and continues to this day in his search for the 'missing ingredient' (15). We visited Dr. Savidov and his system in the summer of 2011, and designed our system using his as a model (16).

In addition, numerous private aquaponic ventures have recently emerged. A few major examples from the Mid-Western US include: Future Farms, was started by Steve Meyer, Chad Hebert and John Vrieze in Baldwin, WI (17). They are dairy farmers that have slowly developed a large and profitable working 'raft' aquaponic system fueled by methane from their animal waste. More recently, they have begun to make the transition away from aquaponics in favor of hydroponic methods. Garden Fresh Farms was created by Dave and Bryan Roesers in Maplewood, MN (18). Their operation is located in an old warehouse, and is totally dependent on artificial light. They have been experimenting with interesting plant growth techniques such as vertical walls and drums rotating around a single tube of light. Nelson and Pade Inc. was founded by Rebecca Nelson and John Pade in Motello, WI (19). They have a working aquaponic system and design/sell aquaponic production systems and system components around the world. They also do a great deal of educational training and coordinate an online aquaponics journal. Growing Power was founded by Will Allen in Milwaukee, WI (20). Growing power's mission is to inspire communities to build sustainable food systems by providing hands-on training, on-the-ground demonstration, outreach and technical assistance. Finally, Urban Organics was founded by Dave Haider and Fred Haberman in 2013, and is located in the old St. Paul, MN Hamm's Brewery (21). They are using a closed loop, recirculating agriculture system to produce a variety of produce exclusively indoors. Each of these operations have an established track record and have become major contributors to advancing aquaponics.

There are also several established aquaponic operations in the Hawaiian Islands. Major examples include: Kunia Country Farms (22), Ili'Ili Farms (23), Mari's Gardens (24), and Living Aquaponics (25). Each of these facilities are designed to take full advantage of the favorable climate by featuring outdoor growth infrastructure. Finally, there are numerous additional aquaponic ventures throughout the US, North America and around the world encompassing a wide variety of scales, methods and years of operation. The number of aquaponic facilities is clearly on the rise.

Version 1.0 – Victus Farms

The University of Minnesota, Duluth's new aquaponic system (27) located in Silver Bay, MN was modeled after the systems described above, but has several key distinctions. The first is our attempt to integrate algae and duckweed into the conventional fish/plant symbiotic relationship. The algae hold the promise of introducing a bio-fuel revenue stream while also serving as a source of valuable oxygen and high protein fish feed. The inclusion of duckweed significantly reduces the need (cost) for external fish feed. Our system is also larger (4x) allowing it to better serve as a research, training and proof of concept facility.

We have received over 1.7 million in funds to date for project feasibility, design, construction, research and early operations. Our major funders share an economic development focus. The aquaponic production system is housed in a 9,000 ft2 Facility. 3,000 ft2 contain a well-insulted building to house the fish tanks and filtration equipment along with a lab, bathroom, utility room and processing area. The other 6,000 ft2 are devoted to an attached greenhouse. The fish are grown in nine 2,000 gallon tanks at high density (up to .5 lbs/gallon). The fish tank water requires constant treatment (60 minute residence time) to prevent O2 depletion, and ammonia toxicity. The fish wastewater flows through four (16 ft x 48ft x 16" deep – 7,500 gallon) troughs to support the hydroponic growth of basil, tomatoes, peppers and lettuce as well as algae and duckweed. Together, the plants, algae and duckweed remove nutrients and add oxygen before it is returned to the fish to complete the cycle. Currently, algae are harvested on only a very small experimental scale, and used to explore various methods of algal harvest, oil separation and biodiesel production as well as their use as a potential direct food source for the fish. Duckweed is also grown and harvested on a very small scale to explore its use as a potential feed source for the fish. Suspended sediments resulting from undigested food and fish feces are re-mineralized within the system. This integrated production system contains approximately 30,000 gallons of water.

We have three primary project outcomes. The first is to demonstrate a local job-creating, economically viable and environmentally sustainable method for producing healthy food and clean bio-fuel. The second is to develop and deliver a range of educational opportunities for a wide variety of potential learners. Educational efforts at the technical college and university level will be aimed at training the workforce required to fuel the anticipated commercial expansion of this concept. The third is to continuously monitor and report system performance as well as develop an interdisciplinary research team to attract funds and conduct research aimed at improving system performance, sustainability and economic viability.

Sustainability

System inputs include heat, electricity, water, fish feed and solar energy. Two biomass biolers (and a backup natural gas boiler) heat the water to 80 degrees F. Electricity use will be offset by a 20 kw wind turbine scheduled for a spring of 2015 installation. Daily water loss (2% or 600 gallons) from evaporation and harvest will be replaced by filtered rainwater stored in large tanks (37,000 gallons) located under the plant and algal troughs. The algal remains (after oil extraction) along with duckweed are used to offset the use of external organic fish feed. Passive Solar Energy is used for space/water heating and growing plants and algae. Future research efforts will be aimed at minimizing these heating, electricity, water and external feed demands, and ensuring renewable energy sources can completely cover these needs. System outputs include only fish, produce and soil. The system generates no waste other than compostable plant, and fish remains after harvest plus any emissions from our natural gas and biomass boilers. In more water scarce environments, any wastewater generated from washing produce could easily be recaptured and treated for use in the system. The system requires no nutrient additives, herbicides, pesticides or hormones. All produce has been organically certified by MOSA, and is sold/delivered daily to local restaurants, grocery stores and individuals. The project is truly a model of sustainable community development.

Economic Viability: Capital and Operational Costs

Our current building/production system requires the following utilities and operational costs: Water use currently averages 7,000 gallons of water per month with approximately 70% supplied by filtered rainwater. The energy required for heating (using natural gas boiler) currently averages 1100 therms per month. In addition, propane is used for supplemental greenhouse heating on an as needed basis. Propane use averages 600 gallons per month for 6 months. Current electricity use averages 5,500 kwh per month. Finally, fish feed inputs average 400 lbs/month with 20% of this coming from algae and duckweed produced internally. Therefore, our current building/production system requires water ($150/month), natural gas heating ($900/month), propane heating ($300/month) electrical ($450/month) and fish feed (Premium Tilapia Pellets) ($400/month) inputs. All utility and feed costs currently total $2,200/month. In addition, we spend approximately $600/month on travel costs to cover the 100 mile round trip from Duluth to Silver Bay five days per week, and $800/month for basic operational maintenance and supplies. Finally, we spend $6,000/month on labor costs. Average total monthly costs sum to $9,600.

Economic Viability: Production and Sales Revenues

We are currently producing 2000 heads (@ $1.25/head) and 200 pounds of lettuce (@ $4/lb), 100 pounds of basil (@$12/lb), 200 pounds of fish (@$4/lb), 100 pounds of tomatoes (@ $3.50/lb), and 100 pounds of cucumbers (@ $1.5/lb). This core production is being sold wholesale to local restaurants and grocery stores. Total sales revenue from this core production sums to $5,700/month. In addition, we have a ‘Saturday Morning Market’ which sells directly to consumers at retail prices approximately 80 heads of lettuce (@ $2.00/hd), 40 ounces of basil (@ $3/ounce), 40 lbs of fish (@$4/lb), 20 pounds of tomatoes (@$4/lb) and 20 lbs of cucumbers (@$2/lb). Direct consumer sales total $560/month. Therefore, average total sales revenues from our current production system sum to $6,260/month and continue to increase steadily as we ramp up production. Several research and operational grants now bridge the gap between our sales revenues ($6,260/month) and our total operational costs ($9,600/month).

Version 2.0 – Wicked Fin Aquatic Farms

New greenhouse and production system design

We have learned a great deal from our first two years of operations at Victus Farms, and have made dramatic improvements in both our production system design and the building that contains it. Using horizontal columns (Image 1) instead of the conventional 'raft' approach (Image 2) improves both growth rates and plant quality. This substitution also allows us to grow approximately ten times more plants per square foot of greenhouse space, and move fish from individual tanks to the growth troughs beneath the horizontal plant columns. These simple improvements eliminate the need for large expensive fish tanks and all their associated plumbing. It also allows us to dramatically reduce the water volume of our overall production system resulting in far less water to circulate and heat. Finally, it reduces the required square footage of our production system by approximately 75%.

In Duluth, MN we have recently designed and constructed a new building to take full advantage of the improvements outlined above (28). This building is far smaller, less expensive and more efficient than our existing facility in Silver Bay, MN. We are currently completing the installation of the new fish/plant production system described above. The building is a very simple 24' x 48' (1,152 ft2) greenhouse. The greenhouse foundation consisted of a concrete perimeter footing (8" high by 16" wide) poured on top of one foot of sand fill. The footing and sand floor was covered using two inch rigid insulation. The insulation was covered with a 6 mil plastic sheet and filled with 4 inches of pea rock. Pex in floor heat tubing was laid out on this pea rock and then covered with another 4-inch layer of pea rock. In floor heating is provided with a conventional 40-gallon hot water heater. Additional space heating and de-humidification is provided by a woodstove as needed. The greenhouse frame was constructed with conventional 2" x 4" treated lumber and trusses were built with the same 2" x 6" lumber. Greenhouse panels were attached to one another with standard 'H' channel and attached to the wooden frame with conventional 1.5-inch barn screws. Two doors and two windows were installed along with fans in each peak for ventilation.

The simplified production system consists of three (10' x 12' x 1') troughs. The troughs will be constructed with two layers of treated 2" x 12''s around the perimeter and lined with a dense pond liner. Each trough will contain 1,000 gallons of water (to support approximately 200 pounds of fish) and have its own simple filtration system as well as an electric in-line heater. Four PVC horizontal column racks (each containing eight ten foot 2" PVC pipes with 12 plant holes each) will be suspended from the ceiling above each trough for lettuce and basil growth. A single pump running 5 minutes every hour will feed trough water into the top of the horizontal columns. The water will cascade through the horizontal column racks and return to the trough below by gravity. Another pump supplies water to 80 feet of 4 inch PVC lines along the south wall of the greenhouse for tomato, pepper and cucumber growth. The production system also contains a 100 square foot warm room for seedlings, and a 36 square foot cold room for produce storage. The warm room (for seed germination and seedling growth) is heated to 78 degrees (normal room temp is approximately 70 degrees) by the heat generated from the grow lights. The cold room (for produce storage) is cooled using a small air conditioner coupled with a 'cool-bot' controller. The processing room consists of some shelving and an 8' double basin stainless steel sink. Supplemental lighting is provided (only needed in 4 winter months) by LED grow lights. Finally, an 800 gallon rainwater storage tank and associated filtration system provides needed water additions to compensate for evaporation and transpiration losses.

Capital and operational costs

The 1,152 square foot greenhouse and the fish plant production system contained within was constructed on a heated gravel floor for under $25,000 plus labor costs. This smaller and far more efficient building/production system will dramatically reduce utility needs and operational costs. Water use will be reduced from 3,500 to 900 gallons of water per month with 80-90% supplied by filtered rainwater. The energy required for heating will be reduced from an annual average of 1100 therms to 300 therms per month. Heating will be supplied by a small electric hot water heater and three in-line electric spa heaters running as needed. Electricity will be reduced from 5,500 to 3,000 kwh per month despite the shift from natural gas and propane to electric heat. Finally, fish feed will be reduced from 400 to 100 lbs/month with an additional 40 pounds per month coming from algae and duckweed produced internally. Therefore, the new building/production system will require only water ($50/month), electrical ($400/month) and food ($100/month) inputs. Total utility and feed costs will be reduced from $2,200/month to $550/month. In addition, travel costs are reduced from $600 to $50/month, and basic operational maintenance and supply costs are reduced from $800 to $400/month. Finally, the labor requirement is reduced to one full time job at a cost of $4,000/month. Total costs for our new production system are reduced from $9,600 to $5,000/month.

Production and Sales Revenues

We expect our new production system will generate: 1200 heads of lettuce (@ $2/head), 40 pounds of basil (@$12/lb) and 80 ounces of basil (@$3/ounce), 120 pounds of fish (@$4/lb), 80 pounds of tomatoes (@$4/lb), 80 pounds of cucumbers (@$2/pound) and 80 pounds of peppers (@$3/pound). This core production will be sold mostly to individuals and groups at retail prices. Total sales revenue from this core production sums to $5,040/month.

A Promising Solution

Therefore, a $25,000 capital investment plus approximately $25,000 worth of expert labor to design, construct, install and train new users generates a facility capable of producing $60,000 per year in fish and produce sales revenues. Of this revenue approximately $12,000 per year covers operational costs leaving $48,000 per year for labor costs. These facilities are showing initial promise that may lead to economic viability, based on minimal fish feed, electrical and water inputs. They generate only rich compost as a waste product. No fertilizers, pesticides, herbicides or growth hormones are required. A production facility can be located in any urban or rural setting as long as electricity, water and sunlight are available. In our cold region, demand for these small-scale local production systems is rapidly intensifying. We have already begun the process of installing similar systems for individuals, restaurants, hospitals, schools and community groups in Northern Minnesota. If it works in Northern Minnesota, it will work anywhere!

References:

1. Plan B 4.0: Mobilizing to Save Civilization. 2009. Lester R. Brown. W. W. Norton and Company. NY, New York.

2. *Sustainable Table* (www.sustainabletable.org).

3. Dara Moskowitz Grundahl, 2013. "After the Oceans". Minneapolis St. Paul Magazine. May. Pgs. 90-96.

4. Timmons M.B., and J.M. Ebelling, 2007. Recirculating Aquaculture. CAYUGA Aqua Ventures. Ithaca, New York.

5. William McLarney (1974). Integration of Garden Vegetables with Fertile Fish Pond Water. The Journal of the New Alchemists. No. 2. 134 pp.

6. William McLarney (1976). Furtheer Experiments in the Irrigation of Garden Vegetables with Fertile Fish Pond Water. The Journal of the New Alchemists. No. 3. 130 pp.

7. William McLarney and Jeffrey Parkin (1979). Open System Fish Culture. The Journal of the New Alchemists. No. 5. 155 pp.

8. William McLarney (1984). The Freshwater Aquaculture Book: A Handbook for Small Scale Fish Culture in North America. 583 pp. Cloudburst Press.

9. McMurtry, M.R. et al. 1997. Efficiency of water use of an integrated fish/vegetable co-culture system. Journal of World Aquaculture Society. Vol 28, No. 4. P. 420-428.

10. McMurtry, M.R. et al. 1990. Sand culture of vegetables using recirculating aquacultural effluents. Applied Agricultural Research. Vol. 5, No. 4. (Fall). Pgs. 280-284.

11. Sanders, Doug, and Mark McMurtry. 1988. Fish increase greenhouse profits. American Vegetable Grower. February. P. 32-33.

12. Rackocy, James E. 1989. Vegetable hydroponics and fish culture: A productive interface. World Aquaculture. September. Pgs. 42-47.

13. Rackocy, James E. 1999. The Status of Aquaponics, Part I. Aquaculture Magazine. July-August. Pgs. 83-88.

14. Rackocy, James E. 1999. The Status of Aquaponics, Part II. Aquaculture Magazine. September-October. Pgs. 64-70.

16. Savidov, Nick. 2011. Personal Communication.

17. Future Farms (www.afuturefarm.com)

18. Garden Fresh Farms (www.gardenfreshfarms.com)

19. Nelson and Pade Inc. (www.aquaponics.com)

20. Growing Power (www.growingpower.org)

22. Urban Organics (www.urbanorganics.com)

23. Kunia County Farms (www.kuniacountyfarms.com)

24. Ili'Ili Farms (www.iliilifarms.com)

25. Mari's Gardens (www.marisgardens.com)

26. Living Aquaponics (www.livingaquaponics.com)

27. Victus Farms (www.victusfarms.org)

28. Wicked Fin Aquatic Farms (www.wickedfin.org)

The Environmental Sustainability of Controlled Environmental Agriculture (CEA)

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I. Introduction:

1. Problems With Conventional Food Production

Global food production is having a hard time keeping up with demand, and trends suggest things are only going to get more difficult (1). Global demand for food is growing as human and grazing animal populations increase, more people are adding more meat to their diets, and more crops are used for biofuel production. On the other hand, it is getting more difficult to continuously increase annual agricultural yields as the downward pressure of soil erosion/degradation, aquifer depletion and irrigation water supply complications due to melting glaciers begins to outpace technological advances in agricultural production (1). We are encountering many problems as we try to meet these challenging trends by squeezing ever more production from our remaining agricultural land.

The majority of our food and animal feed now comes from large-scale industrial crop production using a Mono-cropping approach. This involves growing a single crop over a large area of land. This method became widespread in most industrialized countries in the 1940's and 1950's at the expense of the small family farm as farming became more commodity and less subsistence based. This approach increases mechanization, and demands the use of fossil fuels, fertilizers, pesticides, herbicides, irrigation water and genetic engineering. All of these factors decrease the need for human labor, and ultimately reduce crop prices. While proponents of industrial agriculture claim to have modernized and streamlined the production of food in the United States, such evolution has been at the expense of environmental, human and community health (2).

These industrial farming practices have generated numerous environmental impacts including soil erosion and degradation, water pollution, air pollution and biodiversity loss. These environmental impacts have led to numerous human health problems including ingestion of cancer causing pesticides, herbicides and hormones, increased allergens and anti-biotic resistant bacteria, infectious disease incubation and dispersal and a wide range of respiratory problems from exposure to air pollutants (particulates, Hydrogen Sulfide, Ammonia). Finally, Industrial farms typically import most necessary inputs and export most products leading to local economic stagnation. Surrounding property values also decline significantly as the result of odor, pollution and their associated human health problems. When these local economies degrade their community infrastructure (schools, parks etc…) soon deteriorates as well. In this vicious cycle, environmental and human health problems work together to degrade the communities surrounding these large-scale farming operations (2).

These alarming trends have driven the local food movement. More sustainable food production techniques offer many solutions to the problems with industrial farming, but have difficulty generating year-round, reliable, adequate production (amount and variety) in cold climates. In addition, many of these more sustainable agricultural approaches also require large land areas per unit production, as well as water, energy, nutrient and even chemical additions leading to some of the typical pollution problems associated with conventional agricultural production (3).

Controlled Environmental Agriculture (CEA) approaches such as aquaponics and hydroponics offer the potential to reliably generate large quantities and varieties of food from very small urban spaces in any season. If these food production methods can be made environmentally sustainable and economically viable, this approach could be used in combination with more typical sustainable farming methods to bring us far closer to a more competitive local food system. There are currently many groups in the Midwestern US attempting to do just that (4), and we believe we are very close to developing a sustainable and economically viable CEA approach in Silver Bay, MN at the University of Minnesota, Duluth's Victus Farms (5).

2. Most commonly used CEA production methods:

Interest in CEA has intensified as it becomes clear that this approach has tremendous potential to increase yields, localize food production, minimize the required energy/water footprints and provide a significant sustainable economic development opportunity. Many academic and private CEA efforts/approaches have surfaced in recent years, but there remains a lack of reliable data on CEA yields, inputs/outputs and economic viability, and a consensus on the best possible approaches.

Hydroponics and Aquaponics are the two most popular CEA production methods in use today. Nutrient Film Technique (NFT) and Deep Flow Hydroponics (DFH) are the two most common hydroponic approaches. The nutrient film technique (NFT) was developed during the late 1960's by Dr. Allan Cooper at the Glasshouse Crops Research Institute in Littlehampton, England, and a number of subsequent refinements have been developed since (6). Nutrient solution is pumped to the higher end of each channel and flows by gravity past the plant roots to catchment pipes and a sump. The solution is monitored for replenishment of salts and water before it is recycled. Capillary material in the channel prevents young plants from drying out, and the roots soon grow into a tangled mat. A principle advantage of the NFT system in comparison with others is that it requires much less nutrient solution. It is therefore easier to heat the solution during winter months, to obtain optimum temperatures for root growth, and to cool it during hot summers in arid or tropical regions, thereby avoiding the bolting of lettuce and other undesirable plant responses. Reduced volumes are also easier to work with if it is necessary to treat the nutrient solution for disease control. In 1976, another method, Deep Flow Hydroponics, for growing lettuce or other leafy vegetables on a floating raft of expanded plastic was developed independently by Jensen and Collins (7) in Arizona and Massantini (8) in Italy. Variations of large-scale NFT and deep flow hydroponic production facilities are now common all over the world.

Modern era CEA aquaponics consists of a synergistic relationship between fish and plants. Fish excrete their wastes and plants remove these wastes from solution before the water is returned to the fish. Aquaponics dates back to three key university projects. Mark McMurtry and Doug Sanders from North Carolina State University began their aquaponics system in the mid-1980's. Their system contained tilapia along with tomatoes and cucumbers growing in a sandy medium which doubles as a reciprocating bio-filter. They have used this system to demonstrate sand culturing of plants on fish waste-water (9), water use efficiency (10) and the economic improvements of combined fish and plant operations versus either in isolation (11). Also in the mid-1980's, Dr. James Rakocy developed a modified aquaponic system at the University of the Virgin Islands. Dr. Rakocy added rotating mechanical bio-filters between the fish tanks and the plant growth troughs to replace the sand medium, and developed the first 'raft' aquaponic system. Dr. Rakocy has made numerous contributions (Fish feed, key scaling metrics, nutrient dynamics, pest/disease control, solids removal and bio-filtration) to auquaponic knowledge over the past two decades (12, 13, 14).

More recently, Dr. Nick Savidov, at the University of Alberta's Crop Diversification Center in Brooks Alberta, started an aquaponic system in the mid 1990's modeled after Dr. Rakocy's, but modified for cold-climate applications. Savidov developed a method for recycling all solids in-situ eliminating the difficulties of sediment removal and disposal, and regenerating more internal nutrient to support plant growth. Savidov also demonstrated that plants grew better on fish waste-water than conventional hydroponic nutrient solutions, and continues his search for the 'missing ingredient' (15). We visited Dr. Savidov and his system in the summer of 2011, and designed our initial system using his as a model (15). Finally, we have found the CEA research conducted at the University of Arizona (16) and Cornell (17) University to be extremely useful to the development of our research program. In 1999, after conducting applied CEA research for over a century, Cornell University's CEA Program broke ground on the first commercial scale CEA prototype lettuce production facility in Ithaca, New York. The facility has a production capacity of 1245 heads of high-quality lettuce per day. Researchers at Cornell continue to operate this commercial scale facility and conduct research in the areas of supplemental lighting and commercial hydroponic vegetable production (Cornell University). The University of Arizona's CEA Center (CEAC) was founded by Merle Jensen and is currently directed by Gene Geocomelli. The CEAC opened a modern 5,200 ft2 greenhouse dedicated to CEA research, education and outreach in 2000, and remains a hub of CEA research today.

In addition, numerous private CEA ventures have recently emerged. A few major examples from the US are included below, but there are many others around the world in various developmental stages. Future Farms, was started by Steve Meyer, Chad Hebert and John Vrieze in Baldwin, WI

(18). They are dairy farmers that have slowly developed a large and profitable working ‘raft’ aquaponic system fueled by methane from their animal waste. Garden Fresh Farms was created by Dave and Bryan Roesers in Maplewood, MN (19). Their operation is located in an old warehouse, and is totally dependent on artificial light. They have been experimenting with interesting plant growth techniques such as vertical walls and drums rotating around a single tube of light. Nelson and Pade Aquaponics was founded by Rebecca Nelson and John Pade in Motello, WI (20). They have a working aquaponic system and design/sell aquaponic production systems and system components around the world. They also do a great deal of educational training and coordinate an online aquaponics journal. Growing Power was founded by Will Allen in Milwaukee, WI (21). Growing power’s mission is to inspire communities to build sustainable food systems by providing hands-on training, on-the-ground demonstration, outreach and technical assistance. Urban Organics (22) was founded by Dave Haider and Fred Haberman in St. Paul, MN in 2011. They renovated the former Hamm’s Brewery, and grow produce aquaponically in an entirely indoor facility with artificial lighting. Finally, Gotham Greens (23), founded by Viraj Puri and Eric Haley in 2009 in Brooklyn, NY, may be today’s most successful hydroponic CEA business. They operate over 170,000 ft2 of modern, fully automated, rooftop greenhouses, and have many more projects in the works around the world. They are a leading regional producer of local, premium greenhouse grown produce. Each of these operations above have become major contributors to advancing CEA.

The university research facilities continue to solve numerous challenges facing CEA production with a wide variety of applied research aimed at improving system design and performance, but a clear overall assessment of environmental impacts and economic viability remains difficult to piece together. The numerous successful private CEA operations indicate economic viability is possible with the right approach, but most remain cautious about sharing production methodologies and business financials given the intense competition found in this new and exciting industry. In this paper, we report on the environmental sustainability of three of the most widely used CEA production approaches using data from our work at Victus Farms.

3. Research Summary

We were interested in determining the environmental impacts of three common CEA production methods, and comparing these results with conventional field-based production methods to determine the potential improvements made possible by these CEA production approaches. The CEA production methods examined included: Aquaponic Floating Rafts, Hydroponic Floating Rafts and Hydroponic Vertical Racks. The input requirements examined included: Production space (ft2); Water use (gallons); Electrical use (kwhrs); Natural Gas use (therms); Propane use (gallons); Gasoline use (gallons) Fish feed (lbs) and Nutrients (lbs). No additional inputs (ie., herbicides, pesticides ect…) are required by these three CEA production methods. The three separate experiments were conducted from November of 2013 to October of 2015 using three comparatively scaled production trials. In each trial, the total input requirement from each input category per head of lettuce produced was calculated. We also conducted a literature review to estimate the input requirements of conventional field based lettuce production in California. We compared these input requirements and concluded that each of the CEA methods require far fewer inputs than the conventional California soil based farming methods while eliminating the environmentally problematic nutrient and chemical runoff. Also, we found that hydroponic production requires far less inputs than aquaponic production. Overall, we conclude that CEA holds the promise of a year round, environmentally sustainable produce and protein production approach in cold climates**.**

4. Research Venue: Victus Farms

Victus Farms is the University of Minnesota Duluth’s 1.5 million dollar, 9,000 ft2 CEA production facility. Victus Farms was funded primarily with economic development dollars from the Minnesota State Legislature and began operations in the fall of 2012 with the goal of demonstrating an economically viable and environmentally sustainable method of food production in a cold climate. In addition, Victus Farms serves as an applied research facility aimed at improving the environmental and economic performance of cold-climate CEA production, and an educational facility training students to be future CEA practitioners. This is the second (3) in a series of publications documenting the past 4 years of research in this new CEA production facility.

At Victus Farms we are developing food production methods in a harsh cold climate that minimize required inputs (land, water, energy, nutrient, soil) and eliminate chemicals (herbicides, pesticides, hormones) and polluted runoff. This solution could be widely employed to dramatically increase sustainable economic development while eliminating the air/water pollution and land degradation associated with more conventional agricultural production.

II. Methods

We compared the input requirements of three different, but comparably scaled, produce production methods. These methods include: Aquaponic floating rafts, hydroponic floating rafts and hydroponic vertical racks. The input requirements examined include: Production space (ft2); Water use (gallons); Electrical use (kwhrs); Natural Gas use (therms); Propane use (gallons); Gasoline use (gallons) Fish feed (lbs) and Nutrients (lbs). No additional inputs (ie., herbicides, pesticides ect…) are required by these three CEA production methods. We conclude that all of these methods require far less inputs than even the most sustainable of the conventional soil based farming methods, and that hydroponics requires less inputs than aquaponics.

1. System Design – Aquaponic Floating Rafts

In this approach we use two (16’ x 48’) plant production troughs filled to a depth of 8” to sustain the production of 800 plants/week. This results in a total of 7,582 gallons of water and requires about 1,800 ft2 of greenhouse floor space. In addition, the fish are kept in nine 2000-gallon tanks filled with 1,800 gallons each for a total of 16,200 gallons. The total volume in the troughs and fish tanks equals 23,782 gallons. The water is pumped from each plant production trough to a natural gas powered heat exchanger to the nine fish tanks and then back to each trough on a continuous 24-hour cycle to maintain a 78 degree F temperature. An electric air pump aerates each trough and fish tank on a continuous 24-hour cycle. The plants are grown in 2” net pots placed in holes drilled into 1.5” 2’ x 4’ floating ‘rafts’ made from rigid polystyrene insulation. The holes are spaced to allow 18 plants per 2’ x 4’ floating ‘raft’.

In addition to the approximately 1800 ft2 of greenhouse growing space required to contain the two aquaponic floating raft production troughs, approximately 2,800 ft2 of interior building space is required for fish tanks (2,000 ft2) seedling growth (60 ft2), washing and processing (240 ft2), cold storage (60 ft2) office work (240 ft2) utilities (120 ft2) and a bathroom (80 ft2).

Over a 12-month period from November ’13 to October ‘14 we tracked the production, space, nutrient, water and energy requirements to operate a simple 800 head per week (two 16’ x 48’ troughs) approximately 4,600 ft2 aquaponic floating raft production system. Filtered rainwater was added as needed to maintain water levels in our two 1,895-gallon plant production troughs. Tap water was used to wash the produce. The fish are fed according to their density, age and size. This fish feed serves as nutrient for the plants growing on their wastewater. We attempted to maintain TDS levels in the 200-400 ppm range via our feeding rates. Electricity was used to run the water and air pumps, to provide supplemental lighting to the aquaponic floats and the seedlings. Propane fuel was used to maintain a 50 degree F greenhouse air temperature. Natural gas was used to maintain a 68 degrees F building air temperature. No pesticides or herbicides were added, and there was no runoff or soil erosion from our completely closed production system. In fact, we generated significant soil via composting our plant waste over the course of this experiment. Finally, we also tracked gasoline consumption from delivery miles driven to our local customers.

2. System Design – Hydroponic Floating Rafts

The hydroponic 'floating raft' approach was nearly identical to the aquaponic system described above. Two (16' x 48') plant production troughs were filled to a depth of 4" to sustain the production of 800 plants/week. This results in a total of 3,791 gallons of water and requires about 1,800 ft2 of greenhouse floor space. In addition to the approximately 1800 ft2 of greenhouse growing space required to contain the aquaponic floating raft production system described above, approximately 800 ft2 of interior building space is required for seedling growth (60 ft2), washing and processing (240 ft2), cold storage (60 ft2) office work (240 ft2) utilities (120 ft2) and a bathroom (80 ft2). No floor space or additional water for fish tanks is required with hydroponic production.

Over a 12-month period from January '15 to December '15 we tracked the production, space, nutrient, water and energy requirements to operate a simple 800 head per week (two 16' x 48' troughs) approximately 2,600 ft2 hydroponic floating raft production system. Filtered rainwater was added as needed to maintain water levels in our two 1,895-gallon plant production troughs. Tap water was used to wash the produce. Hydroponic nutrients were added as needed to maintain TDS levels in the 200-400 ppm range. Electricity was used to run the water and air pumps, to provide supplemental lighting to the hydroponic floats and seedlings. Propane fuel was used to maintain a 45 degree F greenhouse air temperature. Natural gas was used to maintain a 60 degrees F building air temperature. No pesticides or herbicides were added, and there was no runoff or soil erosion from our completely closed production system. In fact, we generated significant soil via composting our plant waste over the course of this experiment. Finally, we tracked gasoline consumption from delivery miles driven to our local customers.

3. System Design – Hydroponic Vertical Racks

In the past two years we have experimented with many 'vertical' approaches. Our most successful (in terms of consistent plant production, sustainability and economic viability) 'vertical' hydroponic production system approach to arise from this experimentation is illustrated in figure 1. In this approach two 8' green treat 2" x 4"'s are joined at the top with a hinge that allows us to adjust the space between the 2" x 4"s at the base. Three of these are used to support the 10' 2" PVC pipes. ¼" holes are drilled into the three 2" x 4" 'A Frame' supports every 3", and wooden pegs placed in the holes are used two support the 10' lengths of 2" PVC pipe that run parallel to the floor. Holes (1") are drilled into these PVC pipes spaced every 6" along their length. Plants are placed into these holes, and their roots are free to dangle in the water running through the pipes. The water is pumped from a 112-gallon nutrient reservoir tank on the floor into a 5-gallon plastic bucket suspended above the 'A Frame'. The base of the bucket has several barbs that connect to ¼" irrigation tubing which feeds the top PVC pipe in each 'A Frame'. The water flows by gravity through the eight 10' lengths of PVC pipe along either side of the 'A Frame' and then drains into the nutrient reservoir after exiting the bottom PVC pipe. A Single 'A Frame' can support up to 20 10' 2" PVC pipes with 20 holes per pipe for a total of 400 plants. A set of four 'A Frames' allows ample growing time (4 weeks) for a harvest of 400 plants/week from each set.

Figure 1. Photo of our ‘A Frame’ lettuce racks.

In addition to the approximately 500 ft2 of greenhouse growing space to contain the vertical production system described above, approximately 800 ft2 of interior building space is required for seedling growth (60 ft2), washing and processing (240 ft2), cold storage (60 ft2) office work (240 ft2) utilities (120 ft2) and a bathroom (80 ft2).

Over a 6-month period from March ’15 to August ‘15 we tracked the production, space, nutrient, water and energy requirements to operate a simple 800 head per week (2 sets of 4 racks) approximately 1,300 ft2 (500 ft2 greenhouse, 800 ft2 building) vertical hydroponic lettuce production system. Filtered rainwater was added as needed to maintain water levels in our 112-gallon nutrient reservoir. Tap water was used for produce washing. Hydroponic nutrients were added as needed to maintain TDS levels in the 200-400 ppm range. Electric heating was applied to maintain a 60 degree F water temperature, to run the water and air pumps, to provide supplemental lighting to the vertical racks and the seedling lighting. Propane fuel was used to maintain a 50 degree F greenhouse air temperature. Natural gas was used to maintain a 60 degrees F building air temperature. No pesticides or herbicides were added, and there was no runoff or soil erosion from our completely closed production system. In fact, we generated significant soil via composting our plant waste over the course of this experiment. Finally, we tracked gasoline consumption from delivery miles driven to our local customers.

III. Results

We monitored the space (ft2), water (gallons), electricity (kwhr), natural gas (therms), propane (gallons), gasoline (gallons), herbicide/pesticide and soil requirements for each of the three CEA methodologies described above. The results of each method are reported below as total annual input requirements, and as input requirements per head of lettuce produced.

1. Aquaponic floating raft input requirements:

Land requirements:

Our two 768 ft2 aquaponic floating raft plant production troughs required approximately 1800 ft2 of greenhouse production space. In addition, another 2,800 ft2 of indoor production space was required for the production support activities described for this method above. Total production floor space totaled 4,600 ft2. This system was capable of producing up to 800 heads of lettuce per week, but production of approximately 518 heads/week was the norm. This totaled roughly 26,936 heads per year. Therefore, our hydroponic vertical lettuce production approach required .17 ft2/head.

Water requirements:
Water was lost from our aquaponic floating raft plant production troughs and indoor fish tanks from evaporation, transporation and harvest. In addition, the plant production troughs and fish tanks were filled once initially. These losses varied depending primarily on the greenhouse climate, and proper functioning of our system. Therefore, water was added periodically as needed to our approximately 24,000-gallon production system to compensate for these losses. Over our annual experimental period we added a total of 153,994 gallons. Dividing this annual water usage by our annual lettuce production (26,936 heads) results in an average water requirement of 5.72 gallons per head of lettuce.

Electricity requirements:
The majority of the electrical needs for the aquaponic floating raft production system were for the full-time grow lights in our seedling room, and the seasonal supplemental lighting in our two 768 ft2 plant production troughs. In addition, significant amounts of electricity were needed to run a full-time water pump, drum filter, air pump and seasonal Natural Gas heat pump and a cold-room storage air conditioner. The specific electrical needs for the aquaponic floating raft production system are listed in Table 1.

Equipment	hours/day	watts	#	kwh/day
Seedling Rack LED Lighting	12	165	2	3.96
Seedling Rack T8 Lighting	12	32	8	3.07
Grow Lighting (1000 watt HPS)	3	1000	4	12
Grow Lighting (400 watt HPS)	3	400	12	14.4
Grow Lighting (250 watt LED)	3	240	24	17.28
System Water Pump	24	250	1	6
System Air Pump	24	300	1	7.2
System Natural Gas Heat Pump	9	1000	2	18
Drum Filter Pump	3	1000	1	3
Cold Room Storage Air Conditioner	1	920	1	.92

Total (kwhrs/day)	***85.59***
Total (kwhrs/month)	***2567.76***
Total (kwhrs/year)	***30813.12***

Our hydroponic floating raft production system generated approximately 519 heads of lettuce per week or 26,988 heads of lettuce per year, and required a total of 30813.12 kwhrs/year. This results in approximate annual use of 1.14 kwhrs/hd.

Natural Gas:
Natural gas was used to heat approximately 24,000 gallons of water to 78 degrees F, and approximately 2,800 ft2 of interior building space to 70 degrees F. This resulted in a monthly use of 960 therms of Natural Gas, or 11,520 therms annually. Dividing this annual natural gas usage by the approximate annual lettuce production of 26,936 heads results in a natural gas use of .428 therms per head of lettuce.

Propane:

Propane was used to heat the approximately 1800 ft2 of required greenhouse space to 60 degrees F. This resulted in an average monthly use of 220 gallons, or an annual total of 2640 gallons. Dividing this total propane use by the annual production of 26936 heads resulted in a propane use of .098 gallons per head of lettuce.

Gasoline/diesel requirements:
We delivered all lettuce harvested from our aquaponic floating rafts two times per week. All lettuce was delivered from the University of MN, Duluth to the Duluth Whole Foods Co-op (a distance of 10 miles round trip). The delivery vehicle was a Dodge Grand Caravan with an average fuel efficiency of 25 mpg. Therefore, two trips per week consumed .8 gallons of gas per week, or 41.6 gallons per year. Dividing this annual fuel consumption by our annual lettuce production (26,988 heads) results in .01 gallons per head. No diesel fuel was used.

Pesticide and Herbicide requirements:
No pesticides or herbicides were added, and there was no nutrient runoff or soil erosion from our closed production system. In fact, we generated significant soil (see below) by composting the remains of our lettuce plants after harvest.

Soil Erosion:
Victus farms composts all non-consumable lettuce heads and root systems. Our aquaponic floating raft production system generated approximately 3,500 lbs of organic compost from these inputs per year. Dividing this number by our total annual production from this method (26,936 heads) results in .130 lbs soil per head of lettuce.

2. Hydroponic floating raft input requirements:

Land requirements:
Our two 768 ft2 hydroponic floating raft plant production troughs required approximately 1800 ft2 of greenhouse production space. In addition, another 800 ft2 of indoor production space was required for the production support activities described for this method above. Total production floor space totaled 2600 ft2. This system was capable of producing up to 800 heads of lettuce per week, but production of approximately 512 heads/week was the norm. This totaled roughly 26,624 heads per year. Therefore, our hydroponic vertical lettuce production approach required .1 ft2/head.

Water requirements:
Water was lost from our hydroponic floating raft plant production troughs from evaporation, transporation and harvest. In addition, the troughs were filled once initially. These losses varied depending primarily on the greenhouse climate, and proper functioning of our system. Therefore, water was added periodically as needed to our two approximately 1,895 gallon plant production troughs to compensate for these losses. Over our annual experimental period we added a total of 31,469 gallons. Dividing this annual water usage by our annual lettuce production (26,624 heads) results in an average water requirement of 1.18 gallons per head of lettuce.

Electricity requirements:
The majority of the electrical needs for the hydroponic floating raft production system were for the full-time grow lights in our seedling room, and the seasonal supplemental lighting in our two 768 ft2 plant production troughs. In addition, significant amounts of electricity were needed to run a full-time water pump, air pump and seasonal Natural Gas heat pump and a cold-room storage air conditioner. The specific electrical needs for the hydroponic floating raft production system are listed in Table 2.

Equipment	hours/day	watts	#	kwh/day
Seedling Rack LED Lighting	12	165	2	3.96
Seedling Rack T8 Lighting	12	32	8	3.07
Grow Lighting (1000 watt HPS)	3	1000	4	12
Grow Lighting (400 watt HPS)	3	400	12	14.4
Grow Lighting (250 watt LED)	3	240	24	17.28
System Water Pump	24	120	2	5.76
System Air Pump	24	150	1	3.6
System Natural Gas Heat Pump	5	1000	2	10
Cold Room Storage Air Conditioner	1	920	1	.92

Total (kwhrs/day)	***70.99***
Total (kwhrs/month)	***2129.76***
Total (kwhrs/year)	***25557.12***

Our hydroponic floating raft production system generated approximately 512 heads of lettuce per week or 26,624 heads of lettuce per year, and required a total of 25,557.12 kwhrs/year. This results in approximate annual use of .96 kwhrs/hd.

Natural Gas:

Natural gas was used to heat approximately 3,800 gallons of water to 62 degrees F, and approximately 800 ft2 of interior building space to 65 degrees F. This resulted in a monthly use of 160 therms of Natural Gas, or 1920 therms annually. Dividing this annual natural gas usage by the approximate annual lettuce production of 26,624 heads results in a natural gas use of .072 therms per head of lettuce.

Propane:

Propane was used to heat the approximately 1800 ft2 of required greenhouse space to 50 degrees F. This resulted in an average monthly use of 165 gallons, or an annual total of 1980 gallons. Dividing this total propane use by the annual production of 26,624 heads resulted in a propane use of .074 gallons per head of lettuce.

Gasoline/diesel requirements:

We delivered all lettuce harvested from our hydroponic floating rafts two times per week. All lettuce was delivered from the University of MN, Duluth to the Duluth Whole Foods Co-op (a distance of 10 miles round trip). The delivery vehicle was a Dodge Grand Caravan with an average fuel efficiency of 25 mpg. Therefore, two trips per week consumed .8 gallons of gas per week, or 41.6 gallons per year. Dividing this annual fuel consumption by our annual lettuce production (17,680 heads) results in .011 gallons per head. No diesel fuel was used.

Pesticide and Herbicide requirements:

No pesticides or herbicides were added, and there was no nutrient runoff or soil erosion from our closed production system. In fact, we generated significant soil (see below) by composting the remains of our lettuce plants after harvest.

Soil Erosion:

Victus farms composts all non-consumable lettuce heads and root systems. Our hydroponic floating raft production system generated approximately 3,600 lbs of organic compost from these inputs per year. Dividing this number by our total annual production from this method (26,624 heads) results in .135 lbs soil per head of lettuce.

3. Hydroponic vertical rack input requirements:

Land requirements:

Our eight vertical ‘A Frame’ lettuce production racks and 120-gallon nutrient reservoir required approximately 500 ft2 of greenhouse production space. In addition, another 800 ft2 of indoor production space was required for the production support activities described above. Total production floor space totaled 1300 ft2. This system was capable of producing up to 800 heads of lettuce per week, but production of approximately 340 heads/week was the norm. This totaled roughly 17,680 heads per year. Therefore, our hydroponic vertical lettuce production approach required only .07 ft2/head.

Water requirements:

Water was lost from our vertical ‘A-Frame’ hydroponic lettuce production system from evaporation, transporation, harvest and leakage. These losses varied depending primarily on the greenhouse climate, and proper functioning of our system. Therefore, water was added periodically as needed to our 112-gallon nutrient reservoir to compensate for these losses. Over our annual experimental period we added a total of 2569 gallons for an average of 6.7 gallons per day. Dividing this annual water usage by our annual lettuce production (17,680 heads) results in an average water requirement of .15 gallons per head of lettuce.

Electricity requirements:

The majority of the electrical needs for the vertical hydroponic racks were for the full-time grow lights in our seedling room, and the seasonal supplemental lighting in our plant production racks. In addition, electricity was needed to run an intermittent water pump, full-time air pump and seasonal electric water heater and a cold-room storage air conditioner. The specific electrical needs for the vertical rack production system are listed in Table 3.

Equipment	**hours/day**	**watts**	**#**	**kwh/day**
Seedling Rack LED Lighting	12	165	2	3.96
Seedling Rack T8 Lighting	12	32	8	3.07
Grow Lighting (1000 watt HPS)	3	1000	8	24
Grow Lighting (400 watt HPS)	0	400	6	0
Grow Lighting (250 watt LED)	3	240	8	5.76
System Water Pump	2	240	1	.48
System Air Pump	24	40	1	.96
Electric Wand Heater	4	100	1	.4
Cold Room Storage Air Conditioner	1	920	1	.92

Total (kwhrs/day)	***39.55***
Total (kwhrs/month)	***1186.56***
Total (kwhrs/year)	***14238.72***

Our vertical rack production system generated approximately 340 heads of lettuce per week or 17,680 heads of lettuce per year, and required a total of 14238.72 kwhrs/year. This results in approximate annual use of .81 kwhrs/hd.

Natural Gas:

Natural gas was used to heat approximately 120 gallons of water to 65 degrees F, and approximately 800 ft2 of interior building space to 65 degrees F. This resulted in a monthly use of 90 therms of Natural Gas, or 1080 therms annually. Dividing this annual natural gas usage by the approximate annual lettuce production of 17,680 heads results in a natural gas use of .062 therms per head of lettuce.

Propane:

Propane was used to heat the approximately 500 ft2 of required greenhouse space to 50 degrees F. This resulted in an average monthly use of 60 gallons, or an annual total of 720 gallons. Dividing this total propane use by the annual production of 17,680 heads resulted in a propane use of .041 gallons per head of lettuce.

Gasoline/diesel requirements:

We delivered all lettuce harvested from our racks two times per week. All lettuce was delivered from the University of MN, Duluth to the Duluth Whole Foods Co-op (a distance of 10 miles round trip). The delivery vehicle was a Dodge Grand Caravan with an average fuel efficiency of 25 mpg. Therefore, two trips per week consumed .8 gallons of gas per week, or 41.6 gallons per year. Dividing this annual fuel consumption by our annual lettuce production (17,680 heads) results in .017 gallons per head. No diesel fuel was used.

Pesticide and Herbicide requirements:

No pesticides or herbicides were added, and there was no nutrient runoff or soil erosion from our closed production system. In fact, we generated significant soil (Approximately 5 cubic yards per year) by composting the remains of our lettuce plants after harvest.

Soil Erosion:

Victus farms composts all non-consumable lettuce heads and root systems. Our hydroponic vertical ‘A-frame’ production system generated approximately 2,100 lbs of organic compost from these inputs per year. Dividing this number by our total annual production from this method (17,680 heads) results in .119 lbs soil per head of lettuce.

4. Conventional CA Lettuce Production

In addition to the experimentally derived data described above we attempted to quantify the same input requirements of conventionally field grown CA lettuce. We conducted a literature search of CA lettuce production to try to piece together the data described below. These parameters are difficult to quantify, but these rough estimates obtained from the literature provide a clear contrast to the CEA approaches described above. Data from this section comes from a 2011 detailed historical report from the University of California, Davis’ College of Agriculture and Natural Resources by Richard Smith et al., entitled ‘Leaf Lettuce Production in California’ (24).

Land Requirements:

Smith (24) reports a range of 11 – 13 tons per acre for CA leaf lettuce, and 14.5 – 16.5 tons per acre for romaine. Assuming 2,000 lbs/ton and 1lb/head, this equates to an average annual yield of 24,000 heads per acre for leaf and 31,000 heads per acre for romaine. Therefore, averaging the two types, CA lettuce yields are approximately 27,500 heads per acre, or .63 heads per ft2.

Water Requirements:

Smith (24) reports an average annual irrigation water demand of 12-42 inches per acre on CA lettuce fields depending on location and irrigation methods. The Southern CA desert production regions require far more irrigation water than the central coast and central valley production areas. Also, drip irrigation methods use 20-30% less water than conventional sprinkler systems. Given these considerations, Smith reports a range of 30 – 42 inches per acre in the Southern Desert Region; 18 – 24 inches per acre in the Central Coast Region, and 12 – 18 inches per acre in the Central Valley Region. This is an average of 36, 21 and 15 inches per acre, or 3, 1.75 and 1.25 acre feet. Assuming 325,851 gallons/acre foot, this equates to 977,533, 570,239 and 407,313 gallons per acre. Using our average CA lettuce yield calculated above, we arrive at 35.55, 20.74

and 14.81 gallons of water per head of lettuce. Averaging these regional figures, we calculate a statewide requirement of 21.48 gallons/head.

Nutrient Requirements:

Smith (24) reports a range of N fertilization of 100 -180 lbs N per acre in the Central Coast Region, and 150 – 250 lbs N per acre in the Central Valley and Southern Desert Regions. Averaging across the entire state we calculate 180 lbs/acre. Therefore, assuming an average statewide addition of 180 lbs N/acre to achieve the average yield of 27,500 heads per acre, the Nitrogen requirement would equal .0065 lbs/head.

Smith (24) also reports a range of P fertilization of 50 -100 lbs P per acre in the Central Coast Region, and 200 – 250 lbs P per acre in the Central Valley and Southern Desert Regions. Averaging across the entire state we calculate 175 lbs P/acre. Therefore, assuming an average statewide addition of 175 lbs P/acre to achieve the average yield of 27,500 heads per acre, the P requirement would equal .0064 lbs/head.

Gasoline/diesel Requirements:

In 2001 Etaferchu Takele from the University of California, Davis conducted an economic analysis for loose-leaf lettuce production in California (25). She estimated the on-farm diesel consumption per acre/per year. Assuming a yield of 16,800 heads/acre they estimated on farm consumption of 82 gallons of diesel/acre or .005 gal/head. In addition to on-farm diesel use there is the use for transport to distant markets. As with on-farm use, this is a very difficult and variable number to estimate, but a simple calculation should provide a close approximation. A typical US semi trailer is 48’ x 8’ x 13’ for a total volume of 4,992 ft3. Assuming each head of lettuce requires 1 ft3 of trailer space there are approximately 5,000 heads of lettuce per semi truck trailer. A typical US semi truck gets 6 miles per gallon, and lettuce produced on the west coast makes an average trip of 1,500 miles to supply markets in the US and Southern Canada. Therefore, each truck carrying 5,000 heads of lettuce requires 250 gallons of diesel to make this trip, or .05 gallons/head. Add this transportation use to on-farm use and we have a total diesel requirement of .055 gallons/head.

Electricity Requirements:

Electricity use can also be divided into on-farm use and use in refrigerated transport. We used the UC Davis study (25) as our estimate for on-farm electricity use. They reported a total on farm use of 385 kwh/acre. Assuming total production of 16,880 heads per acre that equals .022 kwh/head. In addition, long distance refrigerated transport consumes considerable electricity. According to the US Governments Energy Star Program, (http://www.energystar.gov/index.cfm?fuseaction=refrig.calculator) a typical refrigerator requires 21.7 kwh/ft2/yr. A typical US semi trailer has a surface area of 2,200 ft2, so it would require 47,740 kwh/yr or 130.8 kwh/d to operate. Assuming an average two-day trip to cover the 1500 miles and 5000 heads of lettuce per trailer that equates to .052 kwh/head. Therefore, total conventional CA lettuce production requires .074 kwh/head.

Pesticide and Herbicide Requirements:

The University of California Agriculture and Natural Resources Program's Statewide Integrated Pest Management Program (UCIPM) suggests the following average herbicide applications per lettuce cohort (27): 1. Follow period: 1.1 lbs/acre of Glyphosphate (Round-up). 2. Preplant: 1.1 lbs/acre of Glyphosphate (Round-up). 3. Pre-emergence: 5.5 lbs/acre of Pronamide (kerb 50W). 4. Post-emergence: .2 lbs/acre of Sethoxydim (Poast 1.5 EC). These suggested applications total 7.9 lbs/acre per lettuce cohort. Assuming four cohorts per year totals 31.6 lbs/acre/year. Given our total annual yield of 16,800 heads/acre we estimate .002 lbs/head. No concise data was available to determine a similar estimate of average annual pesticide additions per head of lettuce.

Soil Erosion:

UC Davis Extension (25) reports annual average rates of soil erosion to be 3.8 tons/acre/yr, or 7,600 lbs/acre/yr. This equates to .175 lbs/ft2/yr. Dividing by the .63 heads/ft2/yr calculated above leaves us with .278 lbs of soil erosion per head of lettuce per year.

5. Summary Table

Table 4 summarizes the required input parameters per head of lettuce produced per year for the three CEA methods and the conventionally grown and distributed CA lettuce.

key Input	Aqua raft	Hydro raft	Hydro vertical	CA Lettuce
Land (ft^2)	.17	.1	.06	.63
Water (gal)	5.72	1.18	.15	22.8
Elec (kwh)	1.14	.96	.81	.074
Propane (gal)	.098	.074	.041	0
Diesel (gal)	0	0	0	.055
Gasoline (gal)	.01	.011	.017	0
Natural Gas (therms)	.428	.072	.062	0
Herbicide (lb)	0.0	0.0	0.0	.002
Soil erosion (lb)	+.13	+.14	+.12	-.19
Nitrogen (lb)		.005	.004	.009
Phosphorus (lb)		.004	.003	.005

all data expressed as per head of lettuce

IV. Discussion

Each CEA method was scaled for approximately 800 heads per week, but actual weekly production experienced dramatic seasonal variation (light, temp, pH, aphids, pythium root rot, organic acid accumulation etc..) over our annual study. Actual weekly production ranged from a low of approximately 120 heads per week to a high of nearly 730 heads per week. In addition, actual production varied between methods from week to week and throughout the year. Although the floating raft approaches consistently provided greater production than the vertical rack approach these production differences were not large enough to significantly impact input requirements. It was beyond the scope of this study to quantify the impacts of these production fluctuations on input requirements, but they would have had only a minor influence on nutrient and perhaps water requirements. All other inputs were required to maintain optimal parameters for growth regardless of actual production amounts. There remains a great deal of potential to more consistently approach the potential 800 head/week harvest target, and even increase this target with tighter plant spacing and achieving shorter growth to harvest periods.

The results reported above clearly indicate that the input requirements decreased significantly as we moved from aquaponic to hydroponic production. Hydroponic production requires far less space and water as well as lower water temperatures. Concentrated organic nutrient additions are far cheaper than organic fish feed, and a more efficient way to deliver nutrients to plants. In our experience, the revenues lost from fish sales were more than offset by the input and labor cost savings. These efficiency gains were increased dramatically with the vertical rack method, but plant production was far less consistent. More work is required to improve consistency of these very promising vertical approaches to growth. Finally, all three of the CEA methods detailed above require far less total inputs than conventional farming. CEA production methods offer a very promising sustainable alternative to conventional farming.

As table 4 indicates, our CEA hydroponic raft production method required far less land (16%), water (5.2%), gasoline/diesel (20%), Nitrogen (55.5%) and Phosphorus (80%) than conventional CA field lettuce production. In addition, the CEA methods required no chemical additions (herbicides, pesticides, fungicides etc…) and resulted in net soil formation (composting) versus significant soil erosion with CA production. These relative input requirements could easily be cut in half with more consistent production per unit input, and with greater production efficiencies (ie. vertical approaches). At Victus Farms, we are still in the early stages of realizing dramatic improvements on both fronts.

However, our CEA hydroponic raft approach required far more electricity (1,297%), than conventional CA field lettuce production (Table 4). In addition, although we could not find a reliable estimate of propane and natural gas use on CA field operations, we assume our CEA methods required significantly more of these inputs as well. We plan to focus our future efforts on reducing our electric and heating needs per unit production, and believe there is tremendous potential to do so. Finally, there are several renewable electricity and heat production alternatives that can be easily incorporated into the CEA production process to further reduce these key input requirements.

CEA practitioners around the world continue to improve their production processes. New production methods such as vertical farming and tighter plan spacing in floating rafts has the potential to dramatically increase production yields per square foot of growth space. Also, understanding and consistently optimizing critical growth parameters has the potential to increase plant harvest weights, and further reduce square footage requirements by decreasing time to harvest. The combination of these two categories of improvements has the potential to reduce these key input requirements per head of lettuce by a factor of four or more. CEA approaches will provide a diverse selection of local, organic year-round produce in cold climates while strengthening local economies and decreasing the environmental impacts of food production.

References:

1. Plan B 4.0: Mobilizing to Save Civilization. 2009. Lester R. Brown. W. W. Norton and Company. NY, New York.

2. Sustainable Table (www.sustainabletable.org).

3. Mageau M.T., et al., 6/23/15. The Aquaponics Solution. May-June. pp 51-59. Solutions Journal. www.thesolutionsjournal.com.

4. Dara Moskowitz Grundahl, 2013. “After the Oceans”. Minneapolis St. Paul Magazine. May. Pgs. 90-96.

5. Victus Farms (www.victusfarms.org).

6. Graves C.J. (1983) The nutrient film technique. Horticutural Review. 5: 1-44.

7. Jensen M.H. and Collins W.L. (1985) Hydroponic vegetable production. Hort. Review 7, 483-558.

8. Massantini F. (1976) Floating hydroponics; A method of soilless culture, 91-98. In Proc. 4th Intn. Congress on Soilless Culture, Las Palmas, Canary Island, Spain.

9. McMurtry, M.R. et al. 1997. Efficiency of water use of an integrated fish/vegetable co-culture system. Journal of World Aquaculture Society. Vol 28, No. 4. P. 420-428.

10. McMurtry, M.R. et al. 1990. Sand culture of vegetables using recirculating aquacultural effluents. Applied Agricultural Research. Vol. 5, No. 4. (Fall). Pgs. 280-284.

11. Sanders, Doug, and Mark McMurtry. 1988. Fish increase greenhouse profits. American Vegetable Grower. February. P. 32-33.

12. Rackocy, James E. 1989. Vegetable hydroponics and fish culture: A productive interface. World Aquaculture. September. Pgs. 42-47.

13. Rackocy, James E. 1999. The Status of Aquaponics, Part I. Aquaculture Magazine. July-August. Pgs. 83-88.

14. Rackocy, James E. 1999. The Status of Aquaponics, Part II. Aquaculture Magazine. September-October. Pgs. 64-70.

15. Savidov, Nick. 2011. Personal Communication.

16. University of Arizona – www.ceac.arizona.edu

17. Cornell University -- http://www.cornellcea.com/

18. Future Farms (www.afuturefarm.com)

19. Garden Fresh Farms (www.gardenfreshfarms.com)

20. Nelson and Pade Inc. - (www.aquaponics.com)

21. Growing Power - www.growingpower.org

22. Urban Organics – www.urbanorganics.com

23. Gotham Greens – www.gothamgreens.com

24. Richard Smith et al., 2011. ‘Leaf Lettuce Production in California’. University of California, Davis’ College of Agriculture and Natural Resources. Publication 7216. http://anrcatalog.ucdavis.edu/pdf/7216.pdf.

25. Etaferchu Takele. 2001. CA Loose Leaf Lettuce Production: Sample Costs and Profitability Analysis. University of California Davis' College of Agriculture and Natural Resources Publication 8031. http://anrcatalog.ucanr.edu/pdf/8031.pdf

26. http://www.energystar.gov/index.cfm?fuseaction=refrig.calculator

27. University of California Agriculture and Natural Resources Statewide Integrated Pest Management Program (UCIPM). http://ipm.ucanr.edu/PMG/r441700411.html#FALLOW