A Study of Aquaponic Systems

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Abstract

This capstone project compares traditional agricultural methods to those of aquaponics. Qualitative research is used to study the effectiveness of aquaponic systems and its ability to solve the financial and environmental impacts of current agricultural methods. This study looks at the environmental, financial, and health impacts of agriculture. Three case studies are used to compare an aquaponic system, aquaculture operation, and an organic farm.

Introduction

As the world's population continues to grow the ability to produce food will become increasingly difficult due to limited water and land supplies. In addition, strain on resources increases as a growing demand for food continues; the ability to produce food as efficiently as possible will be the key to success. The current methods to grow and move food have a noticeable negative effect on air and water quality as well as human health. Alternative food production methods such as aquaponics provides an opportunity to lessen those effects. This paper evaluates the feasibility of aquaponics when compared to the current standard food production method, including some of the monetary costs as well as resources needed such as water, land, and nutrients in relation to the amounts of food produced. Along with the resources used in the different food production methods, this paper compares some of the effects on health that the methods have.

By determining the most efficient food production method for a community, agriculture can progress toward a goal of fully utilizing land, water, and other resources with sustainable practices in mind. Furthermore, certain production methods, such as hydroponics are often considered a practice that can contribute to a healthier environment compared to traditional production methods. Food is a highly political subject and receives large government subsidies to produce food in a manner that might not be considered sustainable. In addition, rising populations are leading to increased food demands and at the same time decreasing access to oil and water sources are causing unpredictability in the food market. Enough food is produced around the world to feed the global population but approximately one billion people or a sixth of the world's population are hungry and an additional billion people do have access to the full daily recommended nutrients (Kremen p.1). This reflects an inability to distribute food in non-industrialized counties.

Aquaponics, which combines fish farming and growing plants without the use of soil, could potentially present a chance for local communities to have more control of the food that they are eating while also presenting savings in the costs of producing that food. One of the benefits of aquaponics is potentially a substantial reduction in the amount of water needed to grow plants as well as additional resources as a system that uses fish waste to provide nutrients to the plants. This results in a potential reduction in the cost of using outside resources to create growth. The integration of plant and fish production also requires less land then if done separately. These systems are typically noted as being more land efficient and are applicable at various scales; they can be used in large scale farming or can be found in a backyard and provide a community with the opportunity to produce more locally grown food.

Literature Review

This paper aims to compare methods of agriculture and food production and to discuss the issues that conventional agriculture faces. In the United States food production in regulated by the United States Department of Agriculture whose vision statement notes that one of its goals is to, "promote agriculture production sustainability that better nourishes Americans" as well as to, "preserve and conserve our Nation's natural resources" (U.S. Department of Agriculture). A key part of the USDA's vision statement is their value of sustainability in food production. Sustainability is defined by the Environmental Protection Agency as, "the conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations" (US Environmental Protection Agency). Agricultural production covers a large amount of land and can often affect soil and water quality in the local ecosystems as well as those many miles away. Agricultural production uses a variety of materials and can have numerous effects on local and regional environments and it is imperative that it becomes more sustainable thereby meeting the food, environmental, and the economic needs of present and future generations.

Agriculture has social, economic, and environmental impacts that vary greatly across the United States. Consumers are no longer only concerned with the price of food but also with its impacts on the environmental and social equity. Due to agriculture's far reaching impacts, sustainability is not an easy task. To plan for sustainability it is necessary to view the world as a system where actions in one area can cause effects in another area (International Institute for Sustainable Development). For example it is possible for rainwater runoff from agricultural fields in parts of the Farm Belt to affect species and environmental quality in the Gulf of Mexico around the mouth of the Mississippi River due to chemicals that were sprayed on crops. The two main nutrients that fertilizers are used to deliver are nitrogen and phosphorus and it is common practice for farmers to use more fertilizer then necessary for security. This excess fertilizer often makes its way into water sources. In the United States that often means the Mississippi River whose watershed makes up 41 percent of the United States; the water that falls on this land eventually makes its way to the Mississippi (Rabalais p. 129). These nutrients promote growth in aquatic life and lead to the growth of algae and phytoplankton which escalate the eutrophication process. Eutrophication is defined as an increase in the supply of organic matter in an ecosystem (Eutrophication). As the supply of organic matter increases, the supply of dissolved oxygen which is necessary to support aquatic life decreases which creates an inhabitable environment. These areas are known as hypoxic zones meaning deprived of oxygen or more commonly referred to as dead zones which, as the name implies, are areas where very little can grow or live. Most of the Mississippi's length is too fast moving for excess algae to grow so the effects of the fertilizers cannot be seen until the river ends in the Gulf of Mexico. The result has been the creation of the second largest hypoxic zone in the world which covered nearly 8,000 square miles in 2001 (Rabalais p. 130). Based on the definition of sustainability, it is imperative to find connections between human actions and development and mitigate for actions that adversely affect our future ability to provide for and meet the world's food needs. When planning for sustainable agriculture, two types of environments need to considered, the local environment and the regional environment, which can be as far-reaching as entire continents.

The definition of an environment can be stated as, "surroundings in which an organization operates. Including air, water, land, natural resources, flora, fauna, humans, and their interrelations" (US Environmental Protection Agency). An organization can be an individual organism or a field of corn or herd of cattle, or an entire river system. A local environment can be seen as the land, water, and air that environmental factors directly affect. The local environment is often affected by land use change such as the draining of wetlands to make space for cropland which can limit the regions ability to filter and clean water as well as lead to an increased risk of flooding.

The regional environment needs to be considered when planning for sustainable agriculture because of agriculture's ability to affect shared resources such as air and water. The USDA's vision statement also includes the goal of, "helping feed others throughout the world" (U.S. Department of Agriculture). Governmental agencies of the United States have made it a goal not just to monitor the needs of US citizens and soil but to help plan and promote the sustainability and health of neighboring nation's citizens, land, water and other resources.

Aquaponics is a method of food production that combines fish and plant production that has only recently begun to be used for commercial purposes. Aquaponics is defined as, "a combination of fish and plant production using aquaculture and hydroponics systems" (U.S. Department of Agriculture). Aquaculture is a method of growing fish in a re-circulating system (Sawyer p.2). Hydroponics is a method of growing plants in nutrient-rich water in a soilless medium (Sawyer p.2). Aquaponics makes use of the natural processes of multiple organisms to reduce the amount of materials needed to grow food. The basics of aquaponics is to raise fish in a tank that circulates water from that tank to a soilless medium where plants are grown. Bacteria growing on the medium convert ammonia and nitrate from fish waste in the water so that plants can absorb those nutrients to grow; the water is then returned to the fish tanks cleaned (Sawyer p.3). Aquaponics presents an opportunity to grow food in a much less land-intensive method as plants and fish can be grown in multistoried buildings, as well as reduce dependence on synthetic fertilizers which use fossil fuels as base ingredients and are energy intensive to manufacture and can have detrimental effects when exposed to water sources. Aquaponics can potentially reduce the unintended side effects that conventional agriculture has in the environment such as the effects that fertilizers have on ground and surface water quality.

Methodology

Before comparing aquaponics with other forms of agriculture it is first necessary to gain a better understanding of current food production practices and the effect of those practices on human health, the environment and financial security. After an underlying understanding in these areas is done, it is necessary to gain an understanding of aquaponics. From here, it is possible to perform a rudimentary comparison of aquaponics to traditional agriculture. The Literature Review contains background information on each of these topics so that there is a basic understanding of the complexities of agriculture as this paper compares different methods of agriculture in the next portion of this paper.

Case studies were used to compare an aquaponics system to a fish farming operation and a farm that grows vegetables. Case studies were used as the comparing element because unpredictability in market prices for food, construction, and labor over time and space make it difficult to set any one numerical amount as the sum of the resources used, making a quantitative approach inconsistent. Since aquaponics combines two food products in its operation a case study for each of those separate products, fish and vegetables, were provided so that the resources needed when these two products are produced separately can be compared to when they are produced in conjunction.

Several themes described earlier were used to qualitatively analyze aquaponics and traditional agriculture. These themes are financial feasibility, sustainability, and healthiness.

Financial feasibility was selected because food prices can determine the kinds of foods that people have access to. Affordable food prices can increase people's access to healthy food which can reduce nutrition related illnesses and feed undernourished populations. Costs of construction, maintenance, and operation determine whether or not food producers will use a particular method of production; if a production method is not financially feasible it is not going to be used. Sustainability was chosen because future resource needs are going to be affected by present consumption. As population grows increased amounts of resources are going to be needed to meet food needs and sustainable food productions used and developed now can potentially insure that resources will be available in the future. Sustainability also includes a food production method's effect on the environment; a method that negatively affects the environment compromises access to resources in the future such as clean water and air. The healthiness of a food includes the overall nutritional content as well as the addition of potentially harmful chemicals through the use of fertilizers, pesticides, and herbicides. The national content of the same type of food can vary based on the way that it was grown so one method can produce a higher quality product while another produces a lower quality product. The use of chemicals to aid in food production has a potential to be harmful the health.

Three case studies were analyzed, one commercial aquaponic system, an operation utilizing aquaculture to raise fish, and an organic farm. A separate fish and vegetable farm were chosen to compare to the two systems at work within an aquaponic system. An organic farm was chosen to compare to the aquaponic system because neither used synthetic fertilizers or pesticides on their crops. The aquaponic system and the fish farming facility both raised Tilapia so space and production could be compared.

Case Study: University of the Virgin Islands

The University of the Virgin Islands (UVI) developed a commercial scale aquaponics system consisting of four fish-rearing tanks and crop space. Each of the fish-rearing tanks holds 2,060 gallons of water ("Recirculating Aquaculture" p.4). Plant growth is dependent on effluent given off by the fish. To calculate the maximum of crops that can be produced it is first necessary to determine the critical standing crop which is the maximum amount of fish that the system can support without restricting fish growth ("Recirculating Aquaculture" p.2). Knowing the standing crop of the fish rearing space is also important because it allows operation at maximum efficiency, producing the maximum amount of fish without wasting materials on fish growth. Tilapia were chosen to be raised because they can tolerate crowding, or a higher number of fish in an area, as well as a greater range of water temperatures and pH levels. Two types of Tilapia were raised, the Nile and Red, and their critical standing crops were found to be 0.51 lbs/gal and 0.59 lbs/gal respectively. It was also found that as a general rule critical standing crop can be assumed to be 0.5 lbs/gal ("Recirculating Aquaculture" p.4). Once the critical standing crop has been determined the amount of crop space can be found; with the UVI system it was found that there ratio of $1ft^3$ of fish-rearing space to $2ft^3$ of hydroponic material to grow crops ("Recirculating Aquaculture" p.9).

The UVI system grew both basil and lettuce as they have relatively short growing periods (3-4 weeks) and commanded higher market prices then other vegetables in the Virgin Islands market. The crops were transplanted into the hydroponic portion of the system so that one-fourth of the crop could be harvested weekly thus providing continual production, after three years of operation the UVI system had produced 148 crops of lettuce ("Recirculating Aquaculture" p.12). Fish harvesting was also staggered to provide a more continuous production, the fish have a 24 week growth cycle so one rearing tank was harvested every six weeks, removing all grown fish and restocking with young fish called fingerlings which were hatched and raised to a few inches in other containers ("Recirculating Aquaculture" p.4). Each fish harvest produced an average of 1,056 lbs. of Nile Tilapia or 1,212 lbs. of Red Tilapia and had an annual production of 9,153 lbs. and 10,516 lbs. respectively. With four tanks each holding 2,060 gallons of waters, a space of 2,303 ft^2 of crop space could be supported which could produce 11,000 lbs. of basil or 1,400 crates of lettuce annually ("Recirculating Aquaculture" p.15). Determining the exact financial viability for an aquaponic system is difficult due to variability in market prices for crops in different locations as well as site specific needs such as temperature control which can add to operational costs. To use a commercial aquaponic system successfully it is necessary to study local operational costs and market price and to select the rearing tank size, fish breed, and crop to maximize space and time in relation to costs.

Case Study: Blue Ridge Aquaculture

Blue Ridge Aquaculture has been producing tilapia since 1993 in Virginia. It is the largest producer of tilapia using indoor recirculating aquaculture systems. The facility produces 4 million pounds of tilapia annually and roughly 75,000 pounds of fish each week (RAS p.12). The recirculating aquaculture systems (RAS) that Blue Ridge uses are very similar to an aquaponic system with the exception of cycling water from the fish tanks through plant beds before it is returned. Recirculating water goes through three steps before it is returned to the fish tanks, the first is solid removal where fish waste and uneaten feed is removed through filtration. Next is bio-filtration where bacteria consume ammonia and convert it to nitrogen, this is the step in aquaponics where plant beds use the nitrogen and other nutrients to grow. Last is oxygenation, the water is re-oxygenated and carbon dioxide is removed (Largest Indoor Fishery).

Blue Ridge Aquaculture's RAS systems use 85% less water than other aquaculture methods due to the use of a recirculating system. It also eliminates the need to be located to a large water source since little water is lost (RAS p.1). The facility has no environmental discharge because the recirculating system and the water that is lost is mostly due to evaporation (Largest Indoor Fishery). Since the systems are recirculating they can be placed in land locked areas, and because they are enclosed, they can be more easily cleaned and placed nearer markets, thereby reducing transportation and providing fresher products. Other aquaculture methods include indoor or outdoor tanks or raising fish in enclosed areas in fresh or saltwater sources such as lakes and oceans. Blue Ridge's products are free of growth hormones, pesticides, and synthetic chemicals, instead relying on selective breeding and nonchemical means, such as temperature and pH levels, to produce healthy fish (RAS p.12). The RAS systems at Blue Ridge Aquaculture are housed in a 100,000 sq. ft. facility that raises fish in roughly 1.5 million gallons of water, the company controls roughly 20% of the US market for live Tilapia (Largest Indoor Fishery).

Case Study: Kestrel Farm

The Kestrel Farm is located in Westminster, Vermont and is a certified organic farm by the Vermont Organic Farmers (Stoner p.6). The farm has 89.5 acres of cultivatable land and grows a variety of crops but this study focuses on the Kestrel Farm's production of lettuce for comparison of its production with that of the aquaponic system at the University of the Virgin Islands. Data from the Kestrel Farm was collected over 2 years, 2002 and 2003, by the Connecticut Agricultural Experiment Station and allows a comparison between the amount of land used and the size of the crop produced between aquaponic systems and an organic farm.

Each year the Kestrel Farm grows lettuce over 10 acres, lettuce is planted over a five week period and picked daily over another 5 week period so that the crop can be shipped to market as continuously as possible (Stoner p.12). The lettuce has a 60 day growing period. The Kestler Farm uses composting to build soil quality rather than synthetic fertilizers and does not spray its fields with pesticides instead using natural predators like ladybugs to cull pest populations. The crop was sampled for pests and it was found that 36% contained infestation of aphids but only 1% of the total yield was lost due to pests (Stoner p.13). The lettuce crop was irrigated by overhead sprinklers so that the crop received 1 inch of water a week (Stoner p.13). The first year that data was collected the farm reduced its weed management practices which may have resulted in a reduced crop yield; weed management practices were increased the second year and there was an increased crop yield (Stoner p.13). An estimated 20% of the lettuce crop was lost each year, usually do to the timing of the harvest leading to immature or over mature lettuce heads being harvested (Stoner p.13). In 2002 the farm averaged a production of 15,200 heads of lettuce per acre and 17,900 heads of lettuce per acre in 2003 (Stoner p.14).

Results and Discussion

When comparing the amount of product produced and the area that was used, the aquaponic system was more efficient then the organic farm and the fish farm. The aquaponic system contained 2,303 sqft of space for growing lettuce and produced roughly 33,600 heads of lettuce annually ("Design and Operation" p.35). The Kestler averaged 16,550 heads of lettuce per acre between 2002 and 2003 (Stoner p.14). The University of the Virgin Islands aquaponic system produced over twice as many heads of lettuce each year but on .05 of the land area. The aquaponic system also produced fish more efficiently then the fish farm at Blue Ridge Aquaculture. At the UVI system Nile Tilapia where raised at .59 pounds per gallon of water ("Recirculating Aquaculture" p.4). Blue Ridge Aquaculture which produces roughly 4 million pounds of Tilapia is raising fish at around .3 pounds per gallon of water which is much less efficient then the UVI system. Based on these case studies the aquaponic was able to out produce the other operations.

Financial Feasibility

Industrialized agriculture is relatively efficient at producing low cost goods. It has accomplished this by altering the natural nutrient cycle through the use of monoculture farms which only raise only one crop. This alteration of the natural nutrient cycle was supplemented by synthetic petroleum based fertilizers to replace nutrients in the soil and the use of pesticides to replace natural predators. In 2012 $15.8 billion in the form of government subsidies is spent on agriculture to cover the rising costs of fertilizers, pesticides, fuel, and other materials needed on a farm in the attempt to curb the costs of food products in the US market. It is also estimated that in the next decade another $90 billion will be spent on farm subsidies (2013 Farm Subsidy Database). Aquaponic systems cannot make use of fertilizers or pesticides since water is shared by both plant and fish and chemicals that may promote growth in one will harm others. However, these resources are generally not needed because aquaponic systems mimic in part a more natural nutrient cycle. Aquaponics reduces or completely eliminates the reliance on many of the materials needed on a monoculture farm which in turn reduces the need of government subsidies to control the market, potentially saving the tax payer billions a year. Aquaponics also presents an opportunity for an increase in local food production as the systems do not depend on environmental factors, such as local soil quality, and can be assembled anywhere that has enough space. This allows many communities to produce locally grown food thus eliminating transportation cost which is another way that food costs can be cut. A study of Chicago's food market indicated that food traveled an average of 1,546 miles before reaching the city (Pirog p.14).

The UVI system has shown that it is possible to operate a commercially sized aquaponic system while turning a profit. By studying local market prices UVI was able to produce food that could be grow quickly and provide as continuous production as possible. Aquaponic systems appears to provide many areas of potential savings that traditional agriculture does not.

Sustainability

The agricultural sector has significant environmental impacts to soil, water, and air quality. Every year trucks transport food throughout the United States using more than 20 billion gallons of oil, thus contributing to the release of carbon dioxide into the atmosphere (Pirog p.3). In the United States carbon dioxide mainly comes from fossil fuel combustion from motor vehicles. Carbon dioxide along with other similar gases contribute to increases in global warming and over 80 percent of global warming potential comes from the combustion of fossil fuels (Pirog p.4). Pollution such as this not only affects the environment but human health as well, in 2005 in California alone there was an estimated 2,400 deaths and an additional 2,800 hospitalizations due to asthma or other similar disease due to exposure to air pollution from freight transportation (Food Miles p.3). The use of chemicals in the growth of food also has significant impacts on the environment; pesticides alone are attributed with over 10 billion dollars of damage to the environment and human health every year (Kremen p.1). Aquaponic systems can easily be placed within greenhouses or even abandoned warehouses or other buildings as they are not reliant on soil quality allowing food to be grown locally, reducing the need to transport food. Aquaponic systems also do not rely on pesticides or other chemicals and the chemicals do not seep into soil or washed into watersheds after a rain.

Healthiness

Aquaponic systems prevent the use of many chemicals to promote growth or prevent pest infestations since a chemical that may be beneficial for the fish may be harmful to the crop. Aquaponic users use none of the chemical methods for preventing pests like the operators at the University of the Virgin Islands, which controlled caterpillar populations by releasing a bacterial pathogen that specifically targeted the caterpillar. The UVI system also prevented fungal infections by manipulating water temperature (“Recirculating Aquaculture” p.12). Plants growing in an aquaponic system are not exposed to many plant diseases which are soil borne and the plants may be more resistant to disease due to the organic matter in the water which creates an environment that many microorganisms grow in, some which may be aggressive towards root pathogens (“Recirculating Aquaculture” p.12).

Pesticides pose both short-term and long-term risks due to exposure that can result in death. Due to the inherent risks in using pesticides, the federal government in the United States regulates the development of pesticides to limit toxicity. The combination of application methods and the cleaning of agricultural product before it is shipped to market has reduced the risk of exposure from consuming food grown with pesticides. The greatest risk of exposure to pesticides and other chemicals used in agricultural production is from contaminated groundwater. In the United States 50% of the population relies on groundwater as their main source of drinking water, but rural areas may be much more susceptible to the effects as 95% of the people in rural areas rely on ground water as their drinking water source (US Environmental Protection Agency).

Conclusion

Agriculture is a necessary component to any nation; as a sector that demands a large quantity of land and resources is important to be as sustainable as possible because of its potential to affect human and environmental health. It has been suggested that aquaponic systems provide the opportunity to produce food in a more resource efficient manner due to its combination of two products whose processes benefit each other and reduce the need for human-supplemented resources to promote growth. Financial success of an aquaponic system is dependent on an operator's ability to study local market conditions to choose the right products and rate of production to remain afloat; this does not differ from any other operation that makes use of a different agricultural method. Aquaponics systems can have a significant advantage over other forms of agriculture in terms of environmental impacts due to their reduced dependency on chemical to aid in growth and their ability to be self-contained systems where chemical byproducts or residue are not exposed to local ecosystems.

Limitations

Cost of construction, upkeep, and price of produce and the viability of using aquaponic systems to produce locally grown food vary due to variability in local markets. This variation of market factors is not just limited to aquaponics but to all agricultural production and it is necessary to evaluate market factors to select location and crops to be financially successful. Aquaponic systems are still in development and there are few systems that produce food commercially. Those in place are relatively small in comparison to many farms that produce food in other ways. The size difference can lead to an inaccurate comparison in resource consumption as larger facilities often reflect savings in resource and energy consumption.

Recommendations

Future analysis of aquaponic systems will need to be conducted as more systems begin to be used commercially so that they can be more accurately compared to more traditional food production methods. Future analysis will also be able to determine aquaponics long-term viability as most systems are relatively young. Increase in aquaponic systems will allow a better understanding of their effect on health, environmental quality, and resource security, and aquaponics benefits and limitations overall.

Bibliography

"2013 Farm Subsidy Database." *EWG Farm Subsidy Database*. Web. 29 Jan. 2015. <http://farm.ewg.org/>.

Buettner, Josh. "Closed-Loop Aquaponic Growing System Combines Land And Lake." Iowa Public Television. Iowa Public Television, 20 Sept. 2013. Web. 21 Nov. 2014.

"Eutrophication." *Definition Page*. Web. 1 Apr. 2015. <http://toxics.usgs.gov/definitions/eutrophication.html>.

Food Miles: How Far Your Food Travels Has Serious Consequences for Your Health and the Climate. Rep. Natural Resources Defense Council, Nov. 2007. Web. 27 Feb. 2015. <https://food-hub.org/files/resources/Food%20Miles.pdf>.

"International Institute for Sustainable Development". *International Institute for Sustainable Development.* Web. 7 Nov. 2014.

Kremen, Claire, Alastair Iles, and Christopher Bacon. "Diversified Farming Systems: An Agroecological, Systems-based Alternative to Modern Industrial Agriculture." *Ecology and Society* 17.4 (2012): n. page. Web. 26 Feb. 2015. <http://www.ecologyandsociety.org/vol17/iss4/art44/>.

"Largest Indoor Fishery - Tilapia, Cobia and Shrimp - Blue Ridge Aquaculture, Inc." *Largest Indoor Fishery - Tilapia, Cobia and Shrimp - Blue Ridge Aquaculture, Inc.* Blue Ridge Aquaculture. Web. 18 Apr. 2015. <http://www.blueridgeaquaculture.com/aboutus.cfm>.

Osteen, Craig, Jessica Gottlieb, and Utpal Vasavada." *Agricultural Resources and Environmental Indicators"*. 2012 ed. Economic Research Service. United States Department of Agriculture, 2012. Print.

Pirog, Rich, Timothy V. Pelt, Kamyar Enshayan, and Ellen Cook. "Food, Fuel, and Freeways: An Iowa Perspective on How Far Food Travels, Fuel Usage, and Greenhouse Gas Emissions." (201): n. pag. Web. 26 Feb. 2015.

Rabalais, Nancy N., R. Eugene Turner, and Donald Scavia. "Beyond Science Into Policy: Gulf Of Mexico Hypoxia And The Mississippi River." *BioScience* 52.2: 129-42. *BioScience*. Web. 1 Apr. 2015. <http://bioscience.oxfordjournals.org/content/52/2/129.full>.

Rakocy, James, Bailey, Donald, Shultz, Charlie, and Danaher, Jason. "Design and Operation of the UVI Aquaponic System." University of the Virgin Islands. , St. Croix. Lecture. Web. 29 Apr. 2015. http://www.uvi.edu/files/documents/Research_and_Public_Service/WRRI/UVIAquaponicSystem.pdf

Rakocy, James, Michael Masser, and Thomas Losordo. *Recirculating Aquaculture Tank Production Systems: Aquaponics-Integrating Fish and Plant Culture*. Southern Regional Aquaculture Center, 2006. Web. 12 Feb. 2015. http://www2.ca.uky.edu/wkrec/454fs.PDF

"RAS Land-Based Recirculating Aquaculture Systems." *Food and Water Watch*. Alliance for Sustainable Aquaculture, 1 Sept. 2009. Web. 18 Apr. 2015. <http://documents.foodandwaterwatch.org/doc/RAS1.pdf#_ga=1.31674942.1619608945.1429325083>.

Sawyer, JD. *Aquaponics: Growing Fish and Plants Together*. Fort Collins: Colorado State U. Print.

Stoner, Kimberly A., and Steve Gilman. *Organic Vegetable Farms in New England-three Case Studies*. New Haven: Connecticut Agricultural Experiment Station, 2008. Print.

"U.S. Department of Agriculture." *U.S. Department of Agriculture*. Web. 7 Nov. 2014.

"US Environmental Protection Agency." *EPA*. Environmental Protection Agency. Web. 7 Nov. 2014.