A NOVEL APPROACH FOR CALCULATING THE FEASIBILITY OF URBAN AGRICULTURE USING AN ENHANCED HYDROPONIC SYSTEM

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DEDICATION

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ABSTRACT

With a continued worldwide trend in population shift from rural to urban areas predicted to increase, new approaches to agricultural production must be considered and implemented. Little academic interest has been applied to determining economically viable urban agriculture crop production sites for business investment. A feasibility model to aid investors in selecting appropriate sites for the development of urban agriculture food production within population centers was created. Lettuce crop trials were performed from August 2015 to December 2015 at the University of Arizona Controlled Environment Agriculture Center to validate the productivity of a unique high density hydroponic system designed for the rooftop environment. The feasibility model is based on this system and with a minimal number of inputs, ranging from size of growing space to growing media costs, determines a wide range of useful outputs. These outputs include crop productivity within the facility, material inputs and a cost breakdown of starting a new agricultural venture. The model utilizes multiple sheets within one excel document to give the user a clear and organized financial perspective of a hypothetical growing operation in the main sheet. With this model, investors into urban agriculture will have a means to gain an objective view of financial considerations before substantial investment is completed.

INTRODUCTION

Sustainable food production and delivery has become a necessity of the modern world. The traditional agricultural structure, involving massive logistical operations to deliver produce into large population centers, uses enormous energy inputs and is becoming less efficient for a world with half of all citizens living in cities (Mengual, Esther, et al., 2013).   Almost all fresh produce consumed in city centers is produced in distant agricultural regions and transported via overland trucking or shipped across oceans (Getter, 2006).

As people have become more aware of the source of their food, consumer trends have shifted, allowing for locally grown produce to be desired by a sizeable portion of the population. This change in buying pattern has been addressed through urban agriculture operations of varying sizes and scopes, the aim of which is to deliver fresh local produce directly to customers, all with minimal transportation costs. According to a report done by the USDA on trends in local and regional food systems, fresh produce buyers are interested in locally grown foods. Not only the source of the food interests consumers but also how it is sold to them. Between 2006 and 2014 the number of farmer's markets in the United States increased 180% to a total of 8,268 while the number of direct to consumer (DTC) sales increased 32% from 2002 to just 2007. Direct to consumer sales are defined, in terms of fresh produce, as any transaction occurring between the producer and the consumer which eliminates the distribution level, such as farmer's markets or road-side stands. More growers are joining the industry to reap the benefits of a sector which the USDA reported the total value in 2012 of $6.1 billion (Low, 2015).

Market interest from investors and governments has increased because of new consumer trends. However, little research has been done to address the specific costs and feasibility associated with an urban agriculture operation and its difference from traditional agricultural models (Mengual, et al., 2013). An economic model which is intuitive enough for an investor, who may not be from the agricultural field, to use while also allowing an experienced grower options to adapt to different locations will be helpful for the emerging urban agriculture sector.

LITERATURE REVIEW

Urban Agriculture (UA)

As the population of the world grew from one billion persons in 1804 to over seven billion people today, the food supply has been struggling to match pace (Leisinger et al., 2002). To meet the demand of the population, farmers shifted into large scale agricultural techniques, employing thousands of acres and the newest technology to increase efficiency and yield. The crop production efficiency rose exponentially as modern and industrial farming techniques overtook traditional, subsistence farming practices. However, to generate food for the rising population, farms could no longer operate within population centers and the rural/urban separation we see today, with agricultural production sites often hundreds of miles from large cities, began to take shape. The distance from field to consumer created the need for new and massive distribution networks. Much more efficient than previous farming techniques, the new production methods did incur logistical costs that are realized both in monetary and environmental terms (Mengual et al., 2013). Although limited in the developed world, this titanic distribution network results in the most urban, often times poorest, inner city areas not receiving proper access to fresh produce at reasonable prices, these are referred to as ‘food deserts’. Urban agriculture is one possible solution to this problem that can bring the fresh produce back to the city center and reduce logistical costs caused by long distance transportation.

Hendrickson defines urban agriculture as “The growing, processing, and distribution of food and other products through intensive plant cultivation and animal husbandry in and around cities” (Hendrickson, 2012). It can involve the use of soil or hydroponic media for plant production, and urban agriculture encompasses all plant and animal production, as long as it is within the city. Urban agriculture is most often distributed locally, with the clear end point being either DTC sales or marketing to a larger local consumer base through food hubs or full-scale distributors who are catering to local businesses/restaurants (Low, 2015).

Many operations that serve the city markets practice organic growing techniques to entice a consumer base which is willing to pay more for these specialty items due to the perceived health benefits with organic certification. While most practice sustainable growing, an organic certification is unobtainable for a new company unless there is significant investor backing. According to a 2011 study by the Food Marketing Institute, knowing the source and production style of an agricultural product was the largest factor for 40% of consumers in their decision to buy locally grown food, second only to freshness of local food (Food Marketing Institute, 2011).

The State of Urban Agriculture

Popularity for local food has been growing steadily over the past two decades. Research into the field has been relatively slow but larger government interest is altering that trend (Low, 2015). Research has been primarily devoted to case studies involving small urban farms in countries outside the United States, and usually in developing parts of the world. These foreign farms are useful to researchers to demonstrate how a food system can benefit from the addition of local agricultural production sites near population centers. Another portion of studies focus on locally grown foods that are delivered to the consumer through DTC sales, farmer's markets, food hubs, or even grocery stores in the United States. The term 'locally grown' can encompass urban agriculture while also representing large farms that sell direct to their consumers and small traditional farms that operate outside of major distribution networks. This section will examine current trends in the urban agriculture marketplace, how those trends came about, and how efficiently farmers are addressing these trends.

Consumers are interested about the source and production method of their fresh produce. The USDA reports that both the value of local food sales and the number of DTC sales are increasing. With an estimated value of 6.1 billion in 2012, the local food industry has more consumers and more producers than ever before (Low, 2015). It is accepted that local food supply chains have higher per unit costs than traditional production means. However, these operations can function efficiently through close-market logistics and eliminating transportation and spoilage costs. Marketing based on the production style (i.e. organic, pesticide-free) in addition to the crop being grown nearby the consumer, can help growers to overcome higher production costs by increasing the cost of their product. Crop diversification, such as having a variety of atypical products, is another strategy employed by successful local farmers to reach a larger market share (King et al., 2010).

Local food demand is highest among persons in urban areas, with the number of local food producers continuing to increase in cities. Due to a rising number of DTC sales opportunities and improved infrastructure for local producers in high population areas, the demand for local produce is beginning to be met (Lichter and Brown, 2011). There has been research done on a number of urban agriculture locations across the globe, all with different motivations and solutions specific to their area in regards to crop production.

Shanghai grew during the 20th century into a city of 24 million citizens, agriculture was pushed away from the city center as land prices increased and development pressed outward. To combat the urban sprawl, the local government began an initiative in the 1990's to increase agricultural production within and surrounding the city. The local government utilized high capital investment in new and efficient agricultural practices to encourage city-wide participation. The city also proposed the idea as a means to have cleaner air and more green spaces within and near the city (Yi-Zhang et. al, 2000). In the following years, UA production has increased heavily with a majority of the items coming from the outer circumference of the city limits while still containing a thriving community-level garden program in the inner city. With demand high and food security risks abundant, mega cities such as Shanghai are heavily involved in urban agriculture, with the United Nations declaring the city 'self-sufficient' as it produces almost all of its agricultural products within its limits (Moreno et al., 2008).

Cuba is a small nation in land mass, and with limited imports, it must utilize urban agriculture as a necessity. With an embargo maintained by the United States for over fifty years and the fall of its ally the Soviet Union in 1989, Cuba embraced a sustainable approach to agriculture, with government backing for projects that allowed citizens to grow their own produce and sell it using communal gardens and programs. One example of these programs is the 'organoponicos' system of government built, raised growing beds that are rented out by growers and are located near city centers and in areas of poor soil. The organoponicos system is just one of many different government-supported strategies used by the Cubans for urban agricultural production (Taboulchanas, 2001). In a study on the effectiveness of urban agriculture in Cuba, researchers found that a society can embrace urban agriculture and produce up to 30% of their food supply through backyard plots, community gardens and other forms of UA production and to overcome food, material, and land shortages (Sanchez, 1997). Urban agriculture has emerged as a viable option for more secure food sources even with cultures as different as Cuba and China.

In recent years, participation in urban agriculture has increased worldwide, with the developed countries of the world expanding rapidly while under-developed portions of the world have remained fairly steady in their agricultural practices near and within city limits. There are approximately 200 million people currently growing agricultural products within urban areas, accounting for nearly 20% of the total global food supply (Armar-Klemesu, 2000). The United Nations estimated that over 800 million people are actively engaged in urban agriculture, either producing, buying, or distributing, and they predict this number to rise as urban areas become more and more populated (Mendes et al., 2008).

Barriers to Entry

New constraints are placed on the UA grower that restrict participation. Large cities have much stricter zoning laws than in rural areas, and in addition property values are magnitudes higher. Production materials are also much harder to supply to an urban based operation due to the natural congestion of the city zone and therefore the profit margin of the final product becomes less.

A major obstacle to urban agriculture has been urban planning and zoning by city governments. Although such laws are useful for the protection and the realities of business operations within cities, they can be hampering to new industries. A study was undertaken in the sub-Saharan city of Dar Es Salaam, Tanzania to determine how much effect the expanding population and land area of the town had on food security. As Dar Es Salaam grew, agricultural production centers began appearing throughout the unregulated zones of town and a new food supply network emerged. From the addition of the new farms, a more stable food supply developed and new zoning protection from city officials aided farmers to profit and maintain their business. With zoning laws in place to prevent land rental from increasing for agricultural sites, farmers were able to keep production costs low and provide citizens with locally sourced fresh produce (Magigi, 2015). Zoning regulation will be a large consideration of large scale urban farming as real estate costs rise and farmers must cope with clearing profit.

Another obstacle for any urban farmer is one of the most basic problems and one that has developed modern agriculture into its current form: location is everything. While a traditional field farmer may grow what best suits his or her location due to the local climate or soil conditions, an urban farmer must create their own environment. Controlled environment agriculture (CEA), such as greenhouse or indoor cultivation, is extremely efficient in producing a crop with less inputs per plant than traditional means but it is inherently very input-demanding. Creating miniature environments in an urban landscape will require a more robust infrastructure to address the increased demand for water, electricity, and waste disposal. Waste disposal and recycling processes exist and have been successful in Sub-Saharan communities for organic wastes from cities to be used in the food production system. Composting and sorting is utilized by the municipalities to create a profitable recycling system of the urban wastes back into the rural agricultural sites, creating new industries while also alleviating waste storage problems. Similar systems could be developed in large-scale urban agriculture to reduce one of the downsides of intensive agriculture (Drechsel, 2001). An increase in water and electrical consumption would also be a side effect of introducing UA to a city on a large scale but municipalities have dealt with increasing infrastructure strain since their inception. Regulation by local governments as to the amount of UA allowed within city limits is one approach to preventing over-use, giving utility management the time to adapt.

Distribution of the final crop is another consideration that may push investment away from urban agriculture. DTC sales at a farmer's market in a city or town can be profitable for smaller growers but for realistic investment into an urban farm the market volume must be sufficiently high and consistent. Historically, the small/local farmer must invest their own time, often without pay, to replace the processing and distribution network that is currently available to traditional agriculture, however, with their unpaid efforts, they replace the "middle men", and thus they collect a much larger share of the retail price. This larger share comes at a hidden cost of unrecorded labor hours and higher transportation costs per unit of produce. These hidden costs are estimated between 13 and 62% of the retail price for overhead in American produce (King et al., 2010).

The market has met these concerns with new, low-volume distributors or 'food hubs' in areas where the local food is in high demand. Regional food hubs (RFH) are, at the most basic level, a low volume distribution system for locally and regionally grown agricultural products, ranging from livestock products to staple crops to niche-market crops. RFH activities can also include marketing, advertisement, and even production advising of the locally produced item. In a 2012 report by the USDA on RFH, they clarify that “A regional food hub is a business or organization that actively manages the aggregation, distribution, and marketing of source-identified food products primarily from local and regional producers to strengthen their ability to satisfy wholesale, retail, and institutional demand.” (Barham et. al). RFH can act as an intermediary between the final marketplace of an item and its producer, thereby eliminating one economic barrier to entry for the grower. In an urban agriculture setting, a RFH is especially useful as it alleviates energy input from several different producers all bringing their crop to market and instead resourcefully pools resources to one bulk pickup/delivery system. RFH also acts to strengthen local and regional food systems by providing a buffer to crop failures through redundant producers who can fill what would be otherwise empty space in a farmer’s market or DTC sale (Low, 2015). With a strong RFH infrastructure, growers have the opportunity to distribute more of their harvest without having to put in the extra labor hours that would be required in DTC sale. The problem of distribution, that RFH’s attempt to solve, appears once there is a marketable crop, and producing that crop is often the largest barrier to entry into urban agriculture.

All new businesses that take advantage of the cutting edge of technology and the newest consumer demands will have large upfront, capital costs, and urban agriculture is no exception. In addition to high property values, all equipment used in a rooftop hydroponic operation must be specifically designed and at greater expense. Thus production values per unit area must be high, construction materials must be lightweight and access must be provided from street level to rooftop. According to the USDA, several states have begun tax incentives for individuals converting unused or run-down plots of major cities into urban agriculture sites. With these tax incentives to new urban agriculture ventures, the capital costs are reduced for an investor of a new urban farm (Low, 2015). City planners can use these tax incentives to bring in new business to a city area that may be seriously lacking an adequate supply of fresh produce and thereby gain community involvement in a project while also eliminating part of a large barrier to entry. Neuner, 2011, described various US projects from Alaska to the Midwest, which required reduced capital costs for urban/local agricultural operations and offered the potential for a healthier community that was more informed and involved with the source of their fresh produce. While federal and local incentives may alleviate some taxes and property costs, a large portion of the startup cost for an urban agriculture facility must still be provided by an investor/owner. These costs are difficult to calculate for those inexperienced in this type of business. This issue will be addressed in this project through the development of an adaptable feasibility model for a UA site.

System Designations

The foremost concern of an urban agricultural operation is space, and the size of the footprint required. Another concern is the weight of the system and the loads that it will create on the building. Therefore the system should be lightweight, to avoid the costs for strengthening the building. Creating an environment suitable for crop production within a dense, urban area will require the installation of greenhouse or indoor growing spaces that must be well suited for the specific climate of the site. All these factors must be considered in the design of the growing system.

There are multiple approaches to the growing system design but to reach the efficiency demanded by the small growing spaces inherent in urban agriculture, hydroponics must be employed. Hydroponics is a soilless culture plant growing method which uses a nutrient solution, containing water and plant fertilizers, to grow the plants with (or without) an artificial root zone medium for support. Hydroponics has been proven to outcompete traditional field agriculture and is the most efficient option, even with its inherent higher capital costs (Jensen, 1985) Closed-loop hydroponics, recirculating of nutrients within a system, use up to 13 times less water than similar crops grown in soil, under controlled environment conditions (Barbosa, 2015). With water conservation becoming a larger concern of agriculture, the water-use efficiency of hydroponics cannot be overlooked. Similarly, the nutrient fertilizer contained in the hydroponic system is absorbed directly by the roots rather than being lost to the open environment in soil or foliar-applied fertilizers common in field style agriculture. A hydroponic system can be designed to optimally grow one crop. Additional benefits of the hydroponic method contained within a controlled environment are resistance to ambient air temperature swings, reduction of water and fertilizer inputs, and the ability to automate operations (Jensen, 1985).

The nutrient delivery system often consists of fertilizer ‘proportioners’, or devices which proportions concentrated nutrient stock solution at designated concentrations as water flows through the mechanism. Proportioners allow the grower to apply a nutrient solution at a designated concentration of water to fertilizer salts depending on the source water and the requirements of the plants to be irrigated (Jensen, 1985). There are several types of hydroponic systems specifically for growing lettuce, including: NFT (nutrient film technique), DWC (deep water culture), and aeroponics, which are the most popular methods. However not all three are suited for UA.

Aeroponics involves the use of high pressure misting systems within a structure containing the roots of crops. Systems often utilize space saving designs such as a-frames and vertical-towers and result in head densities at or above 60 heads per square meter. However, aeroponics involve high pressure pumps which must run at intervals and have the highest complexity of all hydroponic systems mentioned above. They also have the highest initial capital investment and chance for system failure due to the precise nature of the distributor nozzles which can clog easily from non-dissolved salts in the nutrient solution. Although a very efficient growing system option, the complexity of aeroponic systems often restricts the operations willing to invest (Christie et al., 2003).

For a small, short term (under 3 months), leafy crop, NFT can be a good choice. An NFT system consists of gullies or channels that create rows in which the seedlings are placed with their roots bathed by nutrient water which is pumped within the sloped channels from a storage reservoir. The nutrient water is circulated from the storage reservoir to each channel, either continuously or on a timed schedule, and the excess is returned to storage. The flowing nutrient solution creates a thin ‘film’ of water as it passes the roots (Sheikh, 2006).

The NFT approach is most well suited to the leafy greens, such as lettuce and herbs, due in part to high oxygen availability for the partially submerged root mass, and to provide high planting density, and easy access for frequent transplant and harvest. The shallow nature of the nutrient stream flowing within the channel, provides a high surface area to depth ratio, therefore creating high gas exchange at the film surface, increasing dissolved oxygen in the nutrient stream, enabling more vigorous root growth.

Deep water culture (DWC), includes holding tanks filled with nutrient solution that are topped by floating trays which support the plant at the surface of the water with roots fully submerged and the tops above the tray. DWC can function at small levels, with multiple, small volume tanks or in a commercial setting with long raceways, or troughs, which run the length of a greenhouse. The raceway method allows for seedlings to be added at one end while mature heads may be harvested at the far end, creating a constant production line. When space or water weight is not an issue, DWC can be very cost effective.

Despite the simplicity of DWC, it can only grow the crops in one horizontal configuration, whereas NFT can be grown simultaneously at multiple levels, taking advantage of the vertical space. Therefore DWC is less space efficient than high density multi-level NFT designs. High density crop production in this document is defined as greater than fifty heads of lettuce per square meter of growing space. NFT allows the channels to be arranged not only horizontally, but also vertically in a three-dimensional matrix, therefore utilizing not only the footprint of the growing area, but also the volume above. NFT, while requiring more maintenance and technical knowledge than DWC, does offer advantages over aeroponics in that there is a smaller chance of problems arising in the consistency of irrigation (Graves, 1983).

High density hydroponic systems have been in use for decades as the popularity of controlled environment agriculture grew during the 20th century. There has been research performed evaluating specific systems and even determining their financial standings. A recent study involved the creation of a novel hydroponic system which revolved along a vertical oval pattern, dubbed a rotating living wall. Researchers developed the system out of the necessity for a system that operated in a small footprint but maintained the required crop production. The study focused on both the production capacity and hypothetical financial status of an enterprise incorporating the system for production of microgreens (Gumble et al., 2015). These studies focus solely on the characteristics of one system in one, or a small number of scenarios.

The characteristics of the growing area are also of critical concern in urban agriculture projects. Converting the existing structure and space into a growing area without the major overhaul of structure is desired. There are also benefits to the existing building, including a lower thermal load on the building, psychological benefits to the inhabitants of the building, and even reducing noise pollution within the city (Mengual et al., 2013). These benefits can be maximized if the proper original site is chosen that can accommodate the weight and personnel/freight movement that will be increased from having a production site on the roof. The roof must obviously receive ample sunlight throughout the day but also should not be in a location that will expose it to extremely harsh winds. The constraints involved with erecting a greenhouse or similar structure to provide for controlled environment agriculture (CEA) must also be considered when examining a potential space.

The greenhouse revolutionized agriculture and has now become a standard growing method for the world’s most valuable non-commodity crops. Greenhouses with their controlled environments and hydroponic crop production systems primarily produce tomatoes, cucumbers, peppers, and lettuce. They can be found within many companies around the world, optimal environments that will provide for the quickest and most effective growth. There are a myriad of greenhouse structural designs each having benefits and disadvantages, but they all are intended to maintain a stable environment for the plants to grow and flourish, especially within areas of harsh winters and summers. Although vital in many growing applications, greenhouses costs can be the largest factor when considering the feasibility of a project. With the principal goal of light transmission, followed by thermal regulation, the costs for greenhouse temperature regulation can grow by magnitudes during the winter for heating and cooling systems must operate almost non-stop during the summer (Jensen, 1985). Therefore, the greenhouse glazing, or plastic outer covering, must be suited for the location and appropriate insulation from excess heat or cold must be included.

Objectives

The objective of this research was the development of an adaptable cost of production computer model which may be applied to almost any urban area and provide a basic analysis of the economic feasibility of a specific production site. This was accomplished through use of proven capabilities of the novel hydroponic system as a basis for calculating the production parameters of a hypothetical urban agriculture operation. The secondary objectives of the study were to design and construct a high density hydroponic system with appropriate design characteristics for a rooftop, urban agriculture environment; and, to verify its operation and its capability to produce a marketable lettuce crop within a high density hydroponic nutrient film technique system.

MATERIALS AND METHODS

A-Frame Design and Construction

Research to design and construct a high density hydroponic system was conducted at the University of Arizona Controlled Environment Agriculture Center from January 2015 through May 2015. This system was planned for use in the urban agriculture environment, specifically on the rooftops of existing structures.

The hydroponic system was designed and constructed at the ABE fabrication shop at the Campus Agricultural Center with the aid of Charlie Defer, senior fabricator, and Don Clifford. The system would provide the highest growing density in the smallest footprint by utilizing vertical space while also remaining as lightweight as possible to avoid roof reinforcement costs. An ‘A-Frame’ style system employing the Nutrient Film Technique (NFT) was chosen. This hydroponic method allows for maximization of incoming sunlight through sloped sidewalls, while also inherently creating less weight from the small water reservoir. The utilization of the three dimensional space provides greater plant density than other horizontal hydroponic methods, such as floating raft or NFT without an A-Frame.

The design of the A-frame system was comprised of three aluminum trusses. Each truss was constructed of two aluminum struts, each 213 cm, and connected at one end to form an ‘A’-shaped truss. Sixteen 3.81 cm diameter x 305 cm long schedule 40 PVC pipes were attached to each face of the three trusses, to form the three-dimensional A-Frame structure that held 32 plant rows, as seen in Figures 1 and 2. The PVC pipes were connected to the faces of the trusses within the A-frame with aluminum conduit straps and self-tapping screws, and the PVC pipes and A-shaped trusses formed a solid frame. The structure had a footprint of 1.5 x 3.05 m for a total of 6.5 m^2. The PVC pipes were each a row of plants with 2.5cm diameter holes, spaced 15 cm apart for a total of 20 holes per row. The plant row pipes were mounted to provide a 15 x 15cm plant spacing as viewed from overhead.

The plumbing manifold for nutrient water outflow and return was attached to the A-frame, and as indicated in Figure 4. The 416 liter nutrient water reservoir was located beneath the A-frame which provided shade for the tank, reducing algae growth and heating of the nutrient solution, and to effectively utilize the empty space Figure 3. The A-frame was oriented north to south, having an east face and a west face for the plants.

Figure 1. A computer rendering of the a-frame design using Solid Works software.

Figure 2. A view of the East face of the a-frame hydroponic system. Note the holes along the length of each pipe and the first-generation reservoir, later upgraded to a larger tank.

Figure 3. A view of the South face of the a-frame system still under construction, highlighting the aluminum struts forming the support structure of the system which all components are attached to.

Figure 4. The Northern face of the system, the reservoir of the system is placed within the empty space created by the a-frame design. The 416 liter reservoir is insulated with a solar wrap and Styrofoam blocks to limit solar heat gain and to prevent algae growth within the tank.

The plumbing manifold delivered the nutrient solution to the thirty two plant rows with an external circulation pump (Little Giant Pump Co., Oklahoma City, OK) that was plumbed into a 1.9 cm diameter bulkhead fitting in the end of the nutrient water reservoir. The external circulation pump was sized through calculation of total resistance in the system, 3.29 meters and compared to performance curves. A Little Giant '3-md-sc' model was chosen considering the pump capacity is approximately 35 lpm at a head of

3.3 meters and the required flow to the system was calculated to be ~32 lpm. The calculation procedure for the pump sizing can be seen in appendix item iii. The nutrient solution flowed from the circulation pump at approximately 64 lpm up a vertical riser through an inline filter and then split into two manifolds at the peak apex of the A-frame, and then to both of the legs of the southern-facing aluminum trusses. Along the length of the 13 mm diameter manifold pipes were four even spaced pressure regulating flow splitters (Azusa, CA). From each of the splitters, four, 6.5 mm diameter flexible plastic tubes were connected to each of four adjacent plant rows. The inlet manifold along the South face includes a pressure by-pass valve for directing some of the pump flow directly back to the nutrient storage tank and provide flow control for the combined system of plant rows. The flow at each plant row was between 1-2 lpm.

The 3.81cm diameter schedule 40 PVC return line conveyed the nutrient solution drainage from each plant row, after passing through the 20 plant roots contained in the NFT channel, to the reservoir for re-circulation. The A-frame system was situated at a 1:100 elevation loss to allow the nutrient solution to flow from the input manifold, through the tubes, passing the roots before finally returning to the reservoir. The return plumbing was sanitary tees connected individually at the end of each of the plant row PVC pipes which then formed a column extending down the A-frame on the North end. At the bottom the tees trace into one pipeline and eventually flow into a nutrient storage tank (Figure 5). Both the return line and inlet manifold have unions and a ball valve to allow for easy maintenance. The entire system was raised 15 cm to provide room underneath the lowest NFT channel for the return line to have sufficient head into the system without backup. The additional height was added due to the second generation reservoir having a taller upper rim, a trough-style reservoir would be optimal for this system.

Figure 5. View of the return line bulkhead into the reservoir from the North face, a union was placed in-line to allow for simple servicing.

Crop Trials

Crop trials were completed at the University of Arizona Controlled Environment Agriculture Center from September through December 2015. The crop response, electrical power and nutrient solution consumption were recorded to quantify performance characteristics of the system. Environmental conditions, including air temp, PPF, pH, EC, others were monitored…

The experiments were completed within an arch-style greenhouse located at the University of Arizona Controlled Environment Agriculture Center. It is a single bay greenhouse with a footprint of 9.2 x 14.6 m and an apex height of 4.9m. The greenhouse is equipped with air-inflated double layer polyethylene glazing film and 8 mm, acrylic-coated polycarbonate rigid plastic end-walls. The greenhouse utilizes a fan and pad evaporative cooling system consisting of two 3.4 m^3 s^{-1} exhaust fans and an 8.5 m x 1.5m pad. The North-South oriented structure contains an EnviroSTEP environmental controller which monitors air temperature and relative humidity inside an aspirated container (Wadsworth Control Systems, Inc., Arvada, CO). The greenhouse also featured a natural gas-fed hot-air heater located above the evaporative cooling pad on the Northern wall. The A-frame system was located in the Southwest corner of the greenhouse.

The trials tested two factors, including: that the system produced a crop of equal size and quality on both the East and West faces; and, that high density spacing (70+ heads m^{-2}) would not diminish growth in comparison to low density spacing (35+ heads m^{-2}).

All seedlings were started in Jiffy 'Preforma' commercial seedling cubes (Figure 6), which was a mixture of fine peat and a binding agent and has been widely used starter plug in the agricultural industry. The seedlings, each measuring 3.81 x 2.5 x 1.9 cm, were prepared in perforated polystyrene trays measuring 51 x 25 cm, consisting of 105 pre-formed cutouts, with drainage. The seedlings were prepared at a depth of 2 cm into the peat material in crops of 105 seedlings per tray. Once seeded and imbibed with untreated tap water, the trays were placed into the environmental growth chamber located at the University of Arizona's Controlled Environment Agriculture Center. . The growth chamber (Figure 7) air temperature was 18°C for the first three days, then raised to a final temperature of 24°C prior to transplant in the greenhouse. A 295 watt light emitting plasma-based growth light (Stray Light Optical Technologies, Inc.) provided approximately 14,000 lumens at a height of ten inches. The photoperiod selected for germination and seedling maturation was adopted from the Cornell CEA Handbook (Brechner, 2001) and consisted of a twenty-four hour photoperiod for the first eleven days of seedling growth followed by a fourteen hour photoperiod for the remaining three days. Non-fertilized municipal tap water was manually irrigated over the seedling trays once per day using a pump sprayer; a total of 7.57 liters of water were used from the planting of the seedlings until their eventual transplant.

Figure 6. An example of a Rex lettuce seedling grown in Jiffy Preforma material, nine day growth from start of seeding.

Figure 7. The Jiffy Preforma growing material trays were germinated and grown to an age of 14 days inside the environmental growth chamber at the University of Arizona Controlled Environment Agriculture Center.

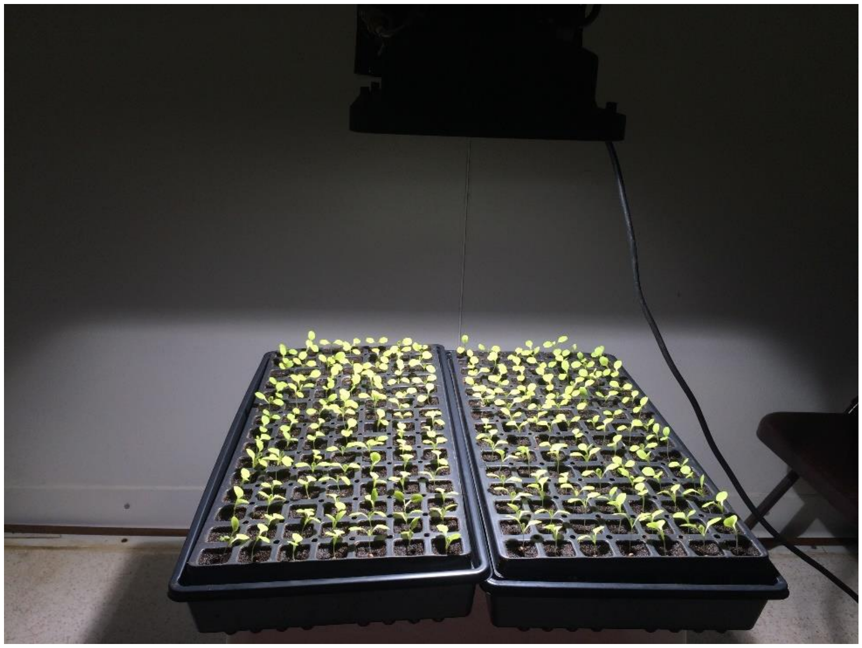


Figure 8. The seedlings were placed at a height of 45.7 centimeters below the light fixture after the initial twenty four hour period inside the growth chamber. What was the PPF?

- First Trial: Small batch of 67 heads, testing general operation of system, 9/3/15 thru 10/15/15
- Second Trial: 165 heads in system, tested equal growth among East/West faces, 9/17/15 thru 11/7/15
- Third Trial: 176 heads in system, increasing density for fourth trial, 10/4/15 thru 11/29/15
- Fourth trial: 205 heads in system, tested ability for rows to be at full capacity, 10/22/15 thru 12/15/15

A crop layout was constructed using Microsoft excel to outline the transplant process and describe placement of heads during each of the four experiments. An experiment is defined as the individual crop trials seeded and transplanted into the system, consisting of two Jiffy trays each. The experiments overlapped in time as the A-frame was never completely filled, and there would be two experiments in parallel in the system during a majority of the time from September to December.

The crop layout document consisted of five timeframes, from the first day after the first experiment had been transplanted in up until the harvest day of the fourth experiment. Each timeframe represents one of the five vertical areas in the excel sheet consisting of one portion stating the date set, one portion describing the layout on the West side and one portion describing the layout on the East side, moving from top to bottom. Within each timeframe, the layout is partitioned the system into East and West faces and further into the rows or tube numbers that make up that face. The layout document was used to accurately test the specific questions surrounding the system with clarity to the researcher and allowed the research to be statistically sound through proper research methods by eliminating possibly confounding variables through confirmation of equal means between faces and spacing layouts of the system.

Transplant of the seedlings to the A-frame system was done fourteen days from the day of seeding, after five in the afternoon to prevent stress to the plants from intense sunlight. According to the crop layout for the specific crop cycle, the seedlings were arranged in either single or ‘every-other arrangement’, i.e., occupying all grow spots in a plant row or occupying every other linear spot. The seedlings were placed into the 2.5 cm diameter holes with 1.3 cm of the grow-cube above the tube and the lower portion situated inside the tube to allow root hydration and prevent excess light entering the tube. Prior to the new transplants, the NFT channels to be used were cleaned and all manifold equipment was flushed. The contents of the reservoir were also examined and the nutrient solution parameters were measured to affirm that the system was ready to receive the new heads.

The parameters of the interior greenhouse climate and nutrient solution were measured using Hanna stationary meters (Hanna Instruments Inc., Rhode Island) or with a CR23x-4m datalogger system (Campbell Scientific Inc., Logan, UT). Measurements were sampled every 10 s and recorded to the datalogger every fifteen minutes for the duration of the experiment. Climate parameters measured included: air temperature (°C), relative humidity (%) and interior PPF (μmol m^{-2} s^{-1}); and, reservoir measurements included: dissolved oxygen content (ppm), electrical conductivity (mS/cm), and pH. The data were downloaded weekly and imported into Excel to be analyzed. The datalogger system accurately determined trends in the aerial climate and the root zone for consistent plant growth.

Four crop harvests were completed during from Sept to Dec 2015 to test specific transplant layouts and to determine quantifiable growth among the lettuce. Ten heads were harvested from each selected row and weighed using. They were then placed into a drying oven for 7 days at 50°C and weighed using an Adventurer analytical scale (Ohaus Corp., Parsippany, NJ) .The first two experiments established that the system could run consistently and, above all, that the east and west faces of the A-frame would produce similar heads and therefore not become a variable in itself. Therefore, the second experiment was transplanted in the same layout on both faces (East and West). The third experiment was completed to both fill the system to a greater capacity and to form a gap between the second and third experiment. The fourth and final experiment evaluated crop response to multiple rows (more than three consecutive rows) and how they may appear in an actual, commercial production, meaning that the a-frame is filled to full capacity.

Confirmation of the validity of the system was done using statistical analysis software SAS (SAS Institute Inc., Cary, NC). ANOVA analyses were performed assuming an alpha, or the probability of rejecting the null hypothesis i.e. believing a 'false positive'], of ($\alpha = 0.05$) and testing a null hypothesis that within specified crop trials there would be no significant statistical difference between the two planting layouts that were being tested. The experiment was completed to test the growth on the East and West faces of the system in the second trial and to test for deficit in growth from cropping multiple rows as single spaced (SS) or full capacity, in comparison to multiple rows in every other (EO), 50% of the row was planted, format. With confirmation of success in the hydroponic system and an effective transplant layout determined, the research shifted to developing the economic investment model.

Economic Model

With the establishment of the A-frame system as a viable growing structure, an economic model of a hypothetical growing operation was initiated. The basis for the model is a simple investment decision aid for an urban agriculture operation that can be applied to various locations, from a limited amount of information inputted.

Introduction

The economic model was built for an investor from most any profession to understand while also providing the experienced grower a robust method for developing a basic cost-analysis of a UA operation. The grower will also input other factors that relate to the greenhouse structure such as weather factors and cooling usage. The model relies on a user-determined number of “crop cycles” per year, or, the number of crop harvests a grower can accomplish within one calendar year. The model displays a financial output spread over a user-determined set of years to alleviate high upfront capital expenditures and to not skew the model for the short term return on investment of fixed costs.

The model has a ‘main’ sheet, which clearly displays inputs, costs, and revenue analysis from several ‘auxiliary’ sheets. The auxiliary sheets include:

- Heating
- Cooling
- Labor
- Additional Materials
- Nutrient Solution Costs
- A-frame build cost

These sheets which supply their calculated results into the main sheet, form the final cost-analysis.

Heating

The heating sheet is the most extensive auxiliary sheet and requires the user to input local climate data for their operation. Using an empirical formula for calculating heat loss from a greenhouse, through the input of climate temperature, set point air temperature inside the greenhouse, and greenhouse construction materials (Eq 1), the energy loss can be calculated each month and summed for the year (Aldrich and Bartok, 1994).

$$Q = U\ x\ SA\ x\ (T_{in,min} - T_{out,min}) \qquad \text{Eq 1}$$

where U =Thermal quality of glazing
SA =Surface area of greenhouse
Tin = Set point temperature inside greenhouse
Tout =Average temperature outside

Labor Sheet

Labor is another auxiliary sheet which uses a per-operation style approach to calculating labor. The approach factors in time spent per activity per crop item, including:

- Delivery
- Marketing
- Seed/Transplant/Harvest/Package
- Production Management
- Maintenance

The labor costs were based on the number of plants involved in each cycle and the number of cycles per year. The user must provide the hourly labor rate and the time required for each task. The time required per task can be determined using direct time study, a method of motion analysis where highly repetitive tasks can be assigned definitive time periods. (Luxhoj and Giacomelli, 1990). With the total number of hours involved per cycle/year calculated, the sheet applies the hourly rate to output a total labor cost in terms of cycle and year.

Nutrient Solution Sheet

The nutrient solution auxiliary sheet calculates the cost per liter of nutrient solution, based on nutrient formulation, and excluding municipal water costs which appear later on the Main sheet. The nutrient solution sheet provides a list of chemicals and their proportions required for a general formulation of a modified Hoagland solution (Hoagland and Arnon, 1950) (See appendix). It includes a cost for each chemical and the calculation of total costs for the maximum use of each stock tank and the cost for a system nutrient reservoir per cycle.

A-Frame Build Sheet

The A-frame build cost sheet outlines all parts necessary for the construction of the A-frame hydroponic system which forms the basis of the financial model. (See appendix) The total build cost for one hydroponic A-frame system is documented and is adjustable to the user based on individual pricing and build preferences.

Cooling Electrical Sheet

Cooling and miscellaneous electrical costs are included in the Cooling Electrical auxiliary sheet. This sheet is used to calculate electrical costs for cooling with ventilation fans while also including an hourly use (kWh) of electrical demands other than exhaust fans. The additional electrical input resulted from the electrical consumption of the nutrient delivery pump of the A-frame system. The irrigation cyclic usage based off number of a-frame systems at the operation and the six week usage, about 230 kWh, of the pump. Calculation of exhaust fan capacity required was based on 2.4 m^3 of air flow per m^2 of growing space (Aldrich and Bartok, 1994). This sheet uses the inputted growing space from the main page and with the user input of exhaust fan yearly usage, and miscellaneous electrical usage per cycle to provide an output of the total electrical cost per cycle and per year.

Additional Materials Sheet

The Additional Materials sheet was to be utilized by the grower as an area to include specialty items that are turned over yearly and must be replaced, such as packaging materials, safety equipment, and backup equipment. The Additional Materials sheet provides these additional costs into the final cost breakdown at the conclusion of the Main page.

Main Page

The Main page of the Excel document combines the values of all the auxiliary sheets along with the production capacity of the system and a cost analysis. The main page is split into five distinct areas:

- Customer Inputs
- Assumptions of the A-frame system
- Facility Designations
- Crop per cycle/year
- Cost Breakdown

The user inputs were made to be applicable to potential investors from non-agricultural backgrounds as well as growers with extensive experience. There are sixteen inputs to the model:

- Available growing space
- Utility costs
- Growing material costs
- Land leasing cost
- Grow cycles per year
- Greenhouse thermal quality
- Greenhouse Surface Area
- Observation period (lifetime of equipment)
- Media costs
- Nutrient solution cost
- Hydroponic system cost to build
- Labor pay rate
- Heating fuel price
- Greenhouse construction cost
- Market price per head

All but two inputs, ‘cost per liter of nutrient solution’ and ‘cost per system’, are available to the grower through the local gas, water/sewer, electrical utility providers, and the local market pricing. The input area of the main sheet is shown in Figure 9.

Figure 9. An example layout of the input section to the main sheet.

The descriptive factors about the hydroponic system and the greenhouse are described in the 'Assumptions of the System' portion of the Main page. This section serves to clarify the source of numbers used in later calculations throughout the spreadsheet. The factors for this area come from the crop trial experiments that were performed. These values may be changed by the user if they would like to compare other growing systems with different capabilities but they are arranged for use in a model incorporating the A-frame hydroponic system. The assumptions for this system include:

- A-Frame Footprint
- Seedlings per Tray
- Water Use per System, per Cycle
- Cycle Duration
- A-Frame Capacity
- Over-Seeding Correction
- Assumed Crop Survival

- Total Number of Cycles Observed

The assumptions of the A-frame system are displayed in Figure 10

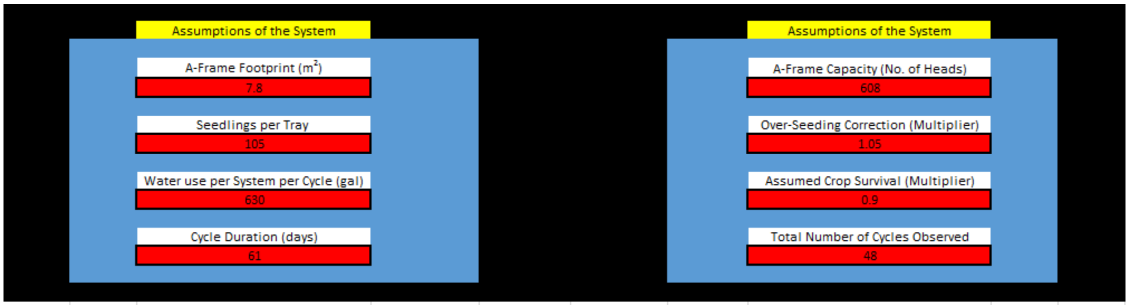


Figure 10. The assumptions of the system as they appear on the Main sheet.

The Facility Designations portion of the Main sheet is derived from previous inputs and other auxiliary sheets. Figure 11 shows the four outputs of the Facility Designations area. This allows for a perspective on the scale of the operation and it includes information such as:

- Number of A-frame Systems
- Exhaust Fans Required
- Labor per Cycle
- Cost for All Systems

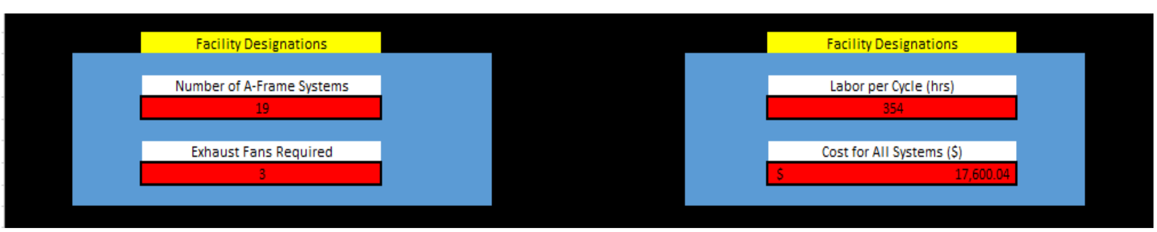


Figure 11. Facility designations of the model which are calculated outputs of previous inputs, on the main sheet.

The Crop Output portion of the Main Page displays the current crop requirements and maximum output to the user after all data inputs are provided. The crop is partitioned into both a cycle and total yearly analysis. The growing media, including seed and trays, is determined from the assumptions of the number of seedlings a seedling tray can grow (ie. capacity of the seedling tray), and the number of heads the facility can produce in a cycle.

The fertigation requirement is calculated from the number of A-frame systems that are within the Facility Designations and the Assumptions Section regarding water use per system. The maximum number of heads for each cycle and per year is determined by the number of heads produced per system and is multiplied by the crop survival rate, typically between 80 and 90% in CEA hydroponics, in the Assumptions of the System section. Figure 12 displays an example production of the crop area of the Main Sheet with an example grow space inputted.

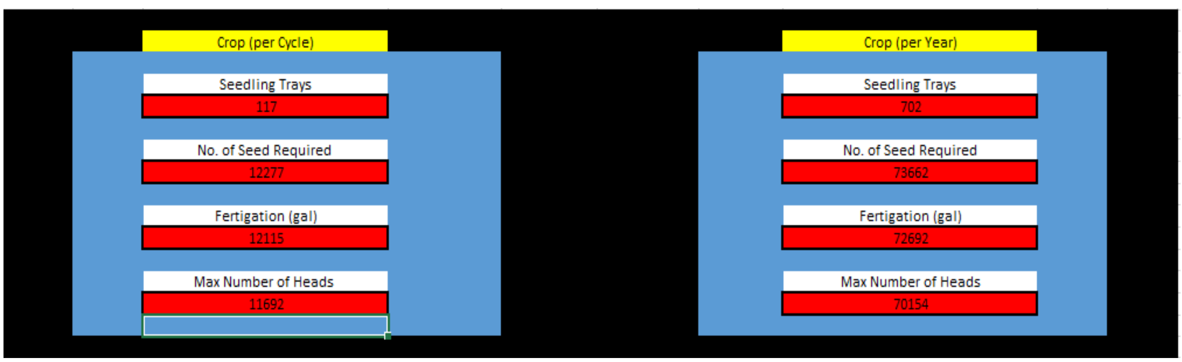


Figure 12. The display of the crop section after calculating a given set of inputs.

The cost breakdown is the final result of the model and crop trials. It displays the variable and fixed costs of a hypothetical urban agriculture operation including the revenue stream, ROI (Return on Investment)/first year investment, sensitivity of yield analysis, and net cash position. The variable costs fluctuate with and are directly related to each production cycle, while the fixed costs remain constant through the observed period. Figure 13 is a hypothetical output of the variable and fixed costs portion of the cost breakdown. The input to the main sheet of 'market price per head' is the largest determining factor in the cost breakdown and allows the user to specify local market conditions and ultimately, determine the feasibility of a site for an urban agriculture facility.

Cost Breakdown

Variable Costs	Item	Number of Units Required per Cycle	Cost/Unit		Cost per Cycle ($)	Cost per Year ($)
	Seed	12277	$ 0.02	($/seed)	$ 245.54	$ 1,473.23
	Trays	117	$ 4.00	($/Tray)	$ 467.69	$ 2,806.15
	Nutrient Solution	12115	$ 0.0109	($/gallon)	$ 132.47	$ 794.84
	Labor	354	$ 8.00	($/hr)	$ 2,831.10	$ 16,986.58
	Heating	74837952	$ 0.48	($/100000 BTU)	$ 359.22	$ 2,155.33
	Electrical/Cooling	2606.67	$ 0.12	($/kw-hr)	$ 312.80	$ 1,876.80
	Additional Materials				$ 436.67	$ 2,620.00
				Total	$ 4,348.82	$ 28,712.95

Fixed Costs	Item	Number of Units Required per Cycle	Cost/Unit		Cost per Cycle ($)	Cost per Year ($)
	Land Rental	150	$ 50.00	($/m^2)	$ 15,000.00	$ 90,000.00
	Greenhouse Construction	150	$ 400.00	($/m^2)	$ 1,250.00	$ 7,500.00
	A-Frame Construction/Materials	19	$ 915.20	($/System)	$ 366.67	$ 2,200.00
	Re-usable Packaging Crates	48	$ 15.00	($/Crate)	$ 15.00	$ 90.00
	Scale	2	$ 100.00	($/Scale)	$ 4.17	$ 25.00
				Total	$ 16,616.67	$ 99,700.00
				All Costs	$ 20,965.49	$ 128,412.95

Figure 13. A typical output of the variable and fixed costs portion of the cost breakdown on the main sheet.

A Year 1 investment analysis was constructed by determining the total capital involvement to a hypothetical area and performing a Return on Investment (ROI) calculation as a percentage of total capital costs from the first year including permanent structures and materials. The total investment analysis is important to all investors to determine the investment risks and rewards of a potential site and give this model more credence to its validity and accuracy. Along with an ROI analysis, net cash position graphs were created in both cycle and yearly view. Figure 14 shows the sensitivity analysis of a hypothetical UA operation. The Sensitivity analysis provides the user with an instant readout of the best/worst case scenario of multiple situations at once through a data table calculation. The data table runs the model for various inputs along an x and y axis orientation that give a profit output. This output shows the profit that may be obtained at various yields and market prices.

Yield Percentage vs Market Price- Profit per Cycle								
$11,133.61	$ 1.50	$ 2.00	$ 2.25	$ 2.50	$ 2.75	$ 3.00	$ 3.25	$ 3.50
100%	$ (11,666.39)	$ (4,066.39)	$ (266.39)	$ 3,533.61	$ 7,333.61	$ 11,133.61	$ 14,933.61	$ 18,733.61
90%	$ (13,105.45)	$ (6,265.45)	$ (2,845.45)	$ 574.55	$ 3,994.55	$ 7,414.55	$ 10,834.55	$ 14,254.55
80%	$ (14,544.51)	$ (8,464.51)	$ (5,424.51)	$ (2,384.51)	$ 655.49	$ 3,695.49	$ 6,735.49	$ 9,775.49
70%	$ (15,983.57)	$ (10,663.57)	$ (8,003.57)	$ (5,343.57)	$ (2,683.57)	$ (23.57)	$ 2,636.43	$ 5,296.43
60%	$ (17,422.63)	$ (12,862.63)	$ (10,582.63)	$ (8,302.63)	$ (6,022.63)	$ (3,742.63)	$ (1,462.63)	$ 817.37
50%	$ (18,861.69)	$ (15,061.69)	$ (13,161.69)	$ (11,261.69)	$ (9,361.69)	$ (7,461.69)	$ (5,561.69)	$ (3,661.69)

Figure 14. An example sensitivity analysis, note the yield percentages along the y axis, the market prices along the x axis, and the profit-per-cycle as the response.

The net cash position graph is a visual of the capital investment throughout time of the operation. The graph, features a monetary y axis with time (in cycles and years) along the x axis. As the hypothetical operation moves through time, starting at the negative cash point of total investment, profits each cycle or year allow the cash point to move to and above the x axis, indicating the business is operating at a profit. Through subtraction of total returns less variable costs from the total investment sum, graphs show the break-even point of the operation over the observed period of time

RESULTS and DISCUSSION

A-Frame Design

The A-frame hydroponic system performed with the only loss occurring due to manifold clogging. The clogging of the manifold was solved with two additions to the system: an inline 50 mesh micron filter placed between the circulation pump and the apex of the riser and more robust pressure-regulating irrigation manifolds. The micron filter screen was cleaned daily to prevent particulates from entering the nutrient solution delivery plumbing. In Figure 15 the addition of the inline filter, the pressure regulating emitters, and the flow-reducing valve can be observed.

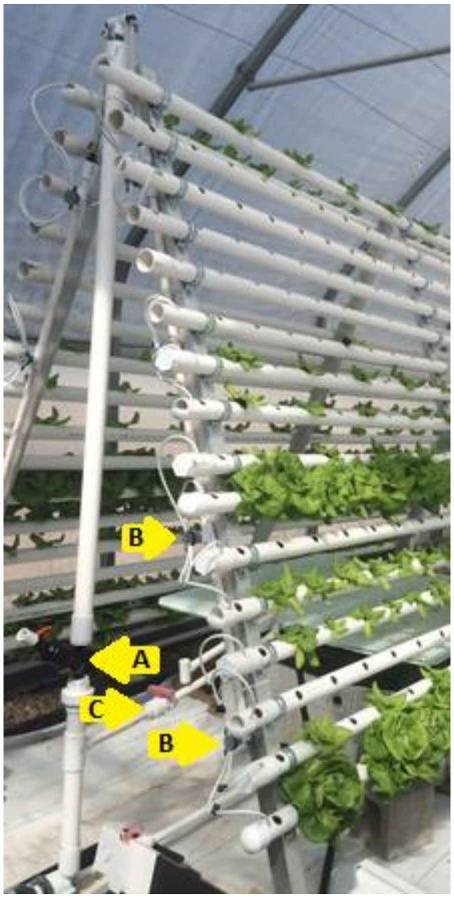


Figure 15. A view of the Eastern face of the system, the inline filter (A) can be seen along the main riser, above the pressure relief valve (C) and pump. One may also note the

pressure-regulating emitters (B) along the diagonal aluminum frame of the system with individual feeder tubes directed into individual channels.

The first experiment identified the size of the reservoir as a critical point of the system. The reservoir must be as large as possible to allow for the consumption of nutrient water. Assuming that there was no automated filling mechanism, daily attention to this was necessary. There was 1.04 L of nutrient water in storage per plant. Peak water consumption was 45 L day^{-1}. Furthermore, as nutrients were consumed, the pH of the nutrient storage water increased to 6.8. . As heads of lettuce grow and absorb nitrate ions into the root system they release a base hydroxyl ion to maintain a neutral level within the roots. This process is usually done at such a rate that the buffering capacity of a hydroponic system's reservoir can maintain a stable pH within the recommended 5.5-6.5 range. However, in a system with such a high ratio of plants to volume of nutrient solution, the release of the base hydroxyl ions can cause large shifts in the pH of the reservoir if water storage volume decreases. At a pH greater than 6.5, certain nutrients become unavailable for absorption by the plants, as shown by Figure 16, causing adverse plant growth effects which can reduce head fresh weight, diminish appearance of green color, and taste. Therefore, the system was refilled daily with fresh nutrient solution, at a slightly more acidic pH of 5.2, and the reservoir was enlarged from 265 liter to 416 liters, therefore increasing the value to 0.7 L per head of lettuce from 1.04 L per head. An automated refill system was considered but ultimately decided against considering daily observations of the system were being conducted regardless of the level insides the reservoir.

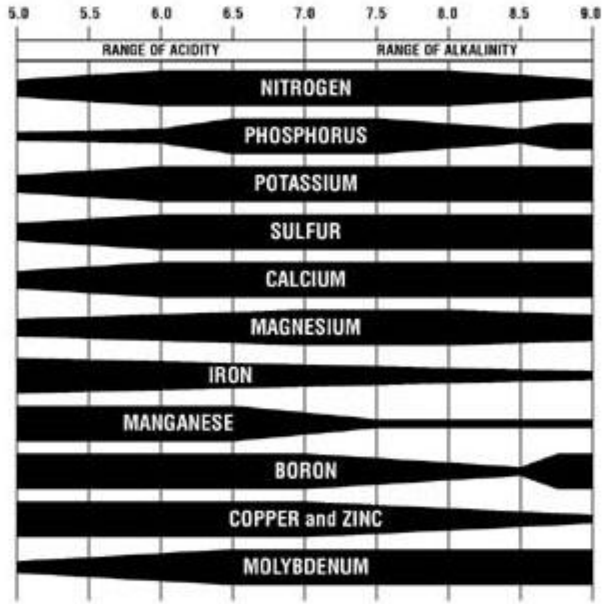


Figure 16. The absorption of macro and micro nutrients varies with pH of the solution, particularly, several micro nutrients such as iron and manganese become nearly at a pH above 7.0. (Kujawski, 2014)

The A-frame system was designed with relatively small 3.81 cm inside diameter PVC pipes, to maximize diagonal space along the A-frame and to minimize shading to the rows of plants beneath each pipe. While highly space-efficient, the narrow diameter presented a problem with the growth of the root mass and required the addition of a bypass valve in the main riser, located immediately after the outlet of the pump. The bypass valve consisted of a plumbing tee from the main riser which directed the pump output flow back into the reservoir. It was controlled by a union ball valve. The gate valve is opened as the plants grew to maturity, allowing for a decrease in nutrient water flow as the root mass increased in the pipe and blocked the flow, and reduced over-flooding of the rows but maintained a thin film of nutrient solution flowing within all of the plant rows.

The final design of the A-frame system had a maximum capacity of 608 heads with a 4.65 m^2 footprint. Incorporating a 30.5 cm 'work area' around the entire perimeter of the A-frame footprint, the hydroponic system occupied 7.8 m^2 and a 2.1 m maximum height at the apex. Including the workspace required for access around each A-frame, the system produced 77 plants m^{-2} which is 44% greater than traditional horizontal growing systems with 43 plants m^{-2} (Hernandez, et al, 2016)

Crop Trials

To quantify the novel system and utilize realistic production values in the economic model, four production trials were performed in the fall of 2015.

First Experiment

The first experiment provided a harvest from four rows of the system. It was completed as a preliminary trial, and it identified the clogging and reservoir issues within the system quickly and allowed the system to be modified and adapted. The layout for the first experiment was according to the crop layout document.

Table 1 is the harvest weights of individual rows and the respective analysis. The first experiment showed relatively uniform growth among the four rows, excluding E7 which experienced a technical clogging failure. Table 2 shows the dry weight analysis of the first experiment and shows less uniformity in average head weight among rows. The graphical representation of the fresh weights and dry weights of the first experiment harvest are shown in Figure 17 & 18, respectively. All improvements to the system were completed during the first experiment and remained unchanged for the remaining experiments.

Table 1. Fresh weight of the first experiment harvest. Rows are represented by face (W=West, E=East) and by number (1 to 16, from bottom to apex). Total head mass (g), Total root mass (g), Average head mass (g) of ten sample size, Average root mass per head (g), Root mass percentage (%) for each of two rows from East side face (E1 & E7), and two rows from West side face (W1 & W6) of the A-frame.

Fresh Weight	W1	W6	E1	E7
Total Head Mass per Row (g)	2135	2260	1955	1010
Total Root Mass (g)	530	565	810	430
Average Head Mass (g)	213.5	226.0	195.5	101.0
Average Root Mass per Head (g)	53.0	29.7	42.6	22.6
Root Mass Percentage (%)	25	13	22	22

Table 2. Dry weight of the first experiment harvest. Rows are represented by face (W=West, E=East) and by number (1 to 16, from bottom to apex). Total head mass (g), Total root mass (g), Average head mass (g) of ten sample size, Average root mass per head (g), Root mass percentage (%) for each of two rows from East side face (E1 & E7), and two rows from West side face (W1 & W6) of the A-frame.

Dry Weight	W1	W6	E1	E7
Total Head Mass / Row (g)	70.9	56.4	82.7	38.9
Total Root Mass (g)	30.4	33.8	32.9	34.5
Average Head Mass (g)	23.6	18.8	27.6	13.0
Average Root Mass per Head (g)	3.00	1.80	1.70	1.80
Root Mass Percentage	13%	9%	6%	14%

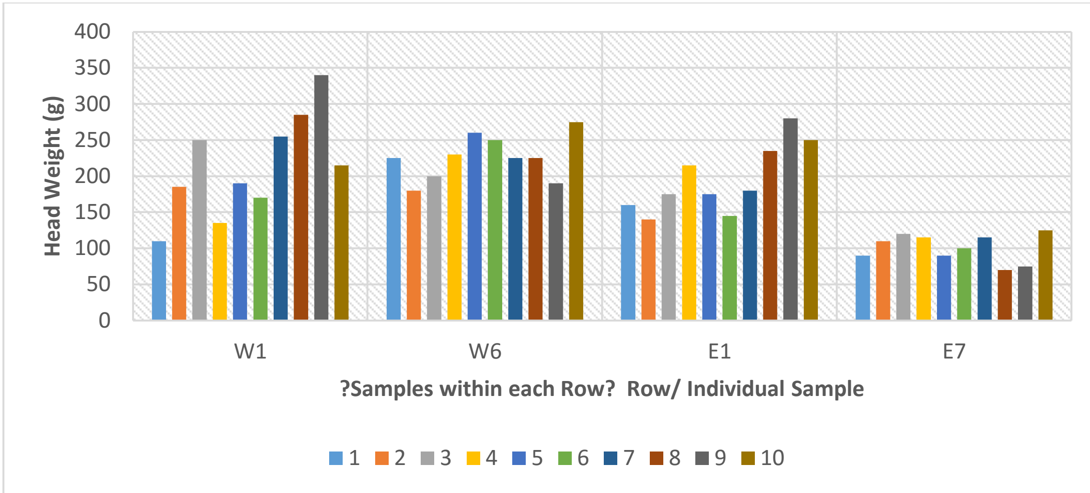


Figure 17. First experiment harvest fresh weights. Each bar represents one of the ten samples from each of four rows.

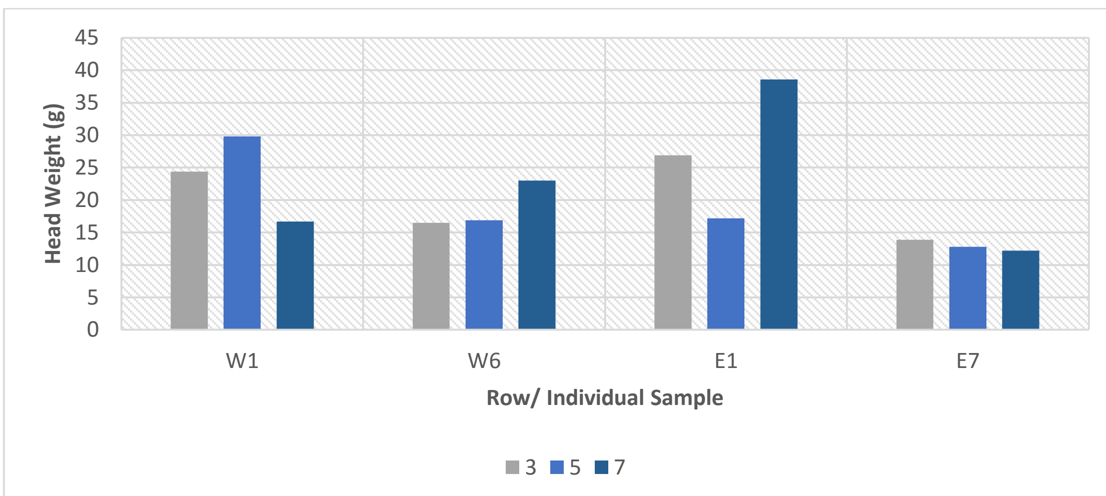


Figure 18. Lettuce Head average dry weight for first experiment. Each bar represents one of the ten samples taken from each row, each grouping of bars represents the weights of a whole row.

Second Experiment

The second experiment included the improved design and operation of the A-frame system, and an increased number of plants from 67 to 165, raising the system capacity from 11% to 38%

With the improvements established from the first experiment, a greater number of plants were successfully grown, having less root zone growing material entering the nutrient stream (use of an inline filter), more uniform flow rate to each row (pressure compensated emitters) and maintaining the nutrient solution pH at desired value (larger reservoir volume and daily addition of fresh water).

The purpose of the second experiment was to demonstrate the uniformity of plant production and crop harvest between the east and west faces of the A-frame. The seedlings were transplanted within nearly identical layouts, (Figure 19) of the heads within and among the rows of each face of the A-frame. There were 12 rows and 10 or 19 plants within each row, depending on spacing pattern designation. An ANOVA statistical analysis (SAS) provided verification that there were no significant statistical differences at 95% confidence between the heads grown on either face. Both ANOVA analyses exhibited p values of 0.85 and 0.30 for the fresh and dry weights, respectively. Figures 20 and 21 are graphical representations of the fresh and dry weights from the second experiment. They indicate a more uniform average head fresh weight across all the rows with a standard deviation under 25 grams for a population of 165 heads. Tables 3 and 4 represent the fresh and dry weights of the second harvest, respectively.

Table 3. Total Head and Root Fresh Mass, and Average Head and Root Fresh Mass for 10 plants in the second experiment harvest. Calculations were done in the same fashion as described in table 1.

Table 4. Total Head and Root Dry Mass, and Average Head and Root Dry Mass for 10 plants in the second experiment harvest. Calculations were done in the same fashion as described in table 1

Dry Weight	W2	W4	W5	W8	w9	w10	E2	e4	e5	e8	e9	e10
Total Head Mass / Row (g)	44	44.2	45.7	45.2	47.6	42.1	46.8	46.02	52	47.6	43.1	43.9
Total Root Mass (g)	18.9	21.4	26.3	21.7	19.0	20.3	22.0	20.4	30.5	17.9	16.5	18.8
Avg. Head Mass (g)	14.7	14.7	15.2	15.1	15.9	14.0	15.6	15.3	17.3	15.9	14.4	14.6
Average Root Mass per Head (g)	1.0	1.1	1.4	2.2	1.9	2.0	2.2	1.1	1.6	1.8	1.7	1.9
Root Mass Percentage	7%	8%	9%	14%	12%	14%	14%	7%	9%	11%	11%	13%

.

Layout from 9/29/15 thru 10/15/15 (1st + 2nd Crop)

Side	Row	Arrangement	Crop #	Heads Needed
West	1	Every Other	1	10
West	2	Single	2	19
West	3			
West	4	Single	2	19
West	5	Single	2	19
West	6	Single	1	19
West	7			
West	8	Every Other	2	10
West	9	Every Other	2	10
West	10	Every Other	2	10
West	11			
West	12			
West	13			
West	14			
West	15			
West	16			
East	1	Single	1	19
East	2	Every Other	2	10
East	3			
East	4	Single	2	19
East	5	Single	2	19
East	6			
East	7	Single	1	19
East	8	Every Other	2	10
East	9	Every Other	2	10
East	10	Every Other	2	10
East	11			
East	12			
East	13			
East	14			
East	15			
East	16			
			Total Heads	232
			Percent Full	38%

Figure 19. All heads under the designation of ‘crop #’ that are labeled with a ‘2’ were from the second experiment and their placement is designated in the above excerpt from the crop layout document. The spacing style (Single or Every Other) and the subsequently required number of heads (10 or 19) is also specified.

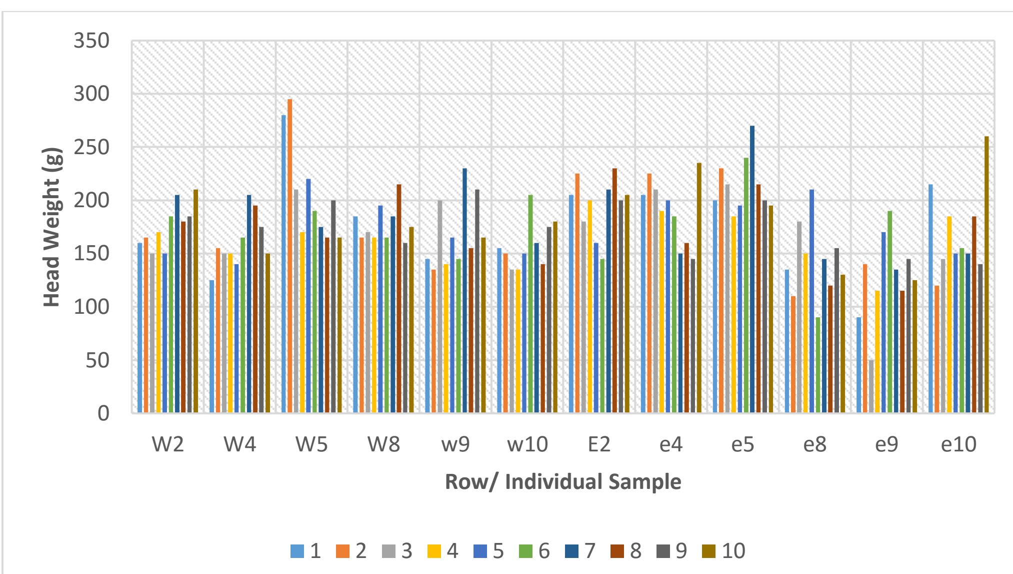


Figure 20. Fresh lettuce head weight for 10 samples (1 – 10) from the second experiment for each row number (2 through 10), and each face (East (E) or West (W)).The colors within each grouping represents the different rows.

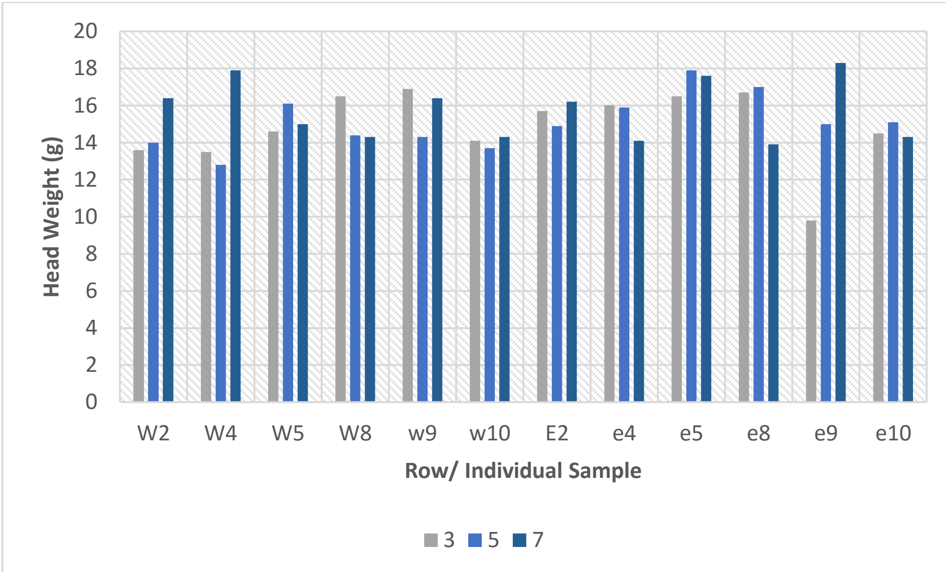


Figure 21. Dry lettuce head weight for 10 samples (1 – 10) from the second experiment for each row number (2 through 10), and each face (East (E) or West (W)). The colors within each group represents the different rows.

Third Experiment

The third experiment tested greater plant density and raised the system production capacity from 38% to 63%, as shown in the crop layout document, by increasing the number of plants from 165 to 176.

Harvest for the third experiment was delayed 7 days compared to the Second Experiment to study increased head size and overcrowding between plants to determine if a larger head size would be attainable in the current system. No detriment to plant growth from factors such as mold, abnormal shoot growth, or root growth problems were observed. However, by allowing the plants to grow beyond the market weight of 150 grams, did cause problems with overflow of nutrient solution from the PVC grow tubes and subsequent loss of solution and flooding.

With the delay of harvest, the lettuce head fresh weights were more inconsistent between rows than previous experiments, with a standard deviation among all rows of 70 grams for 176 heads compared to 85 for previous. A delayed harvest, was applied to the system, the greater head mass and higher variation among rows was seen as useful data and could be used in future research to adapt the system to larger grow cycles. Figures 22 and 23 display this difference of growth among rows graphically and in comparison to figures 20 and 21, show the greater standard deviation. Tables 5 and 6 are the fresh and dry weights of the third experiment harvest, respectively.

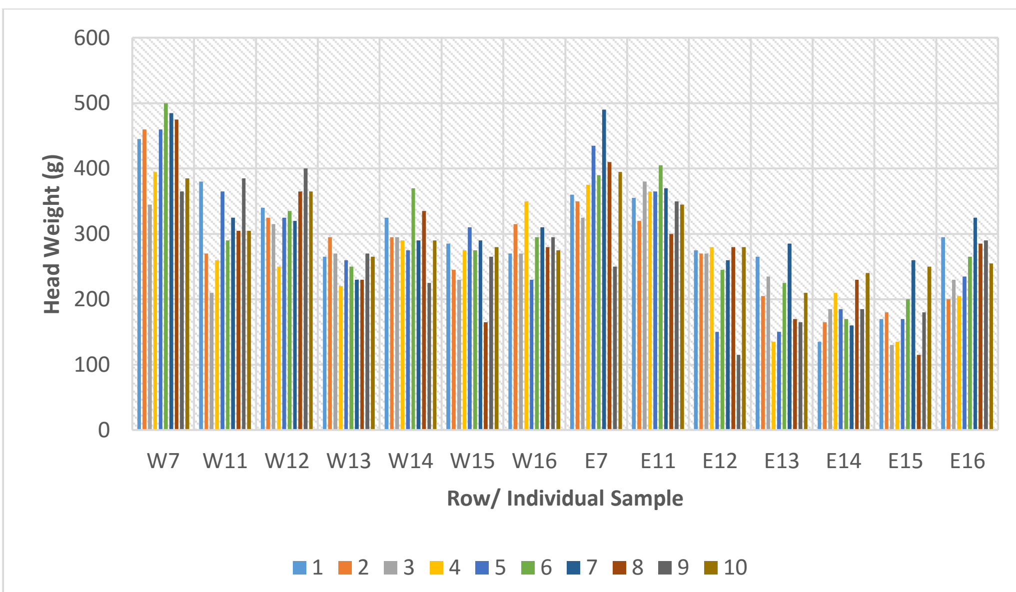


Figure 22. Fresh lettuce head weight for 10 samples (1 – 10) from the third experiment for each row number (7 through 16), and each face (East (E) or West (W)).The colors within each grouping represents the different rows.

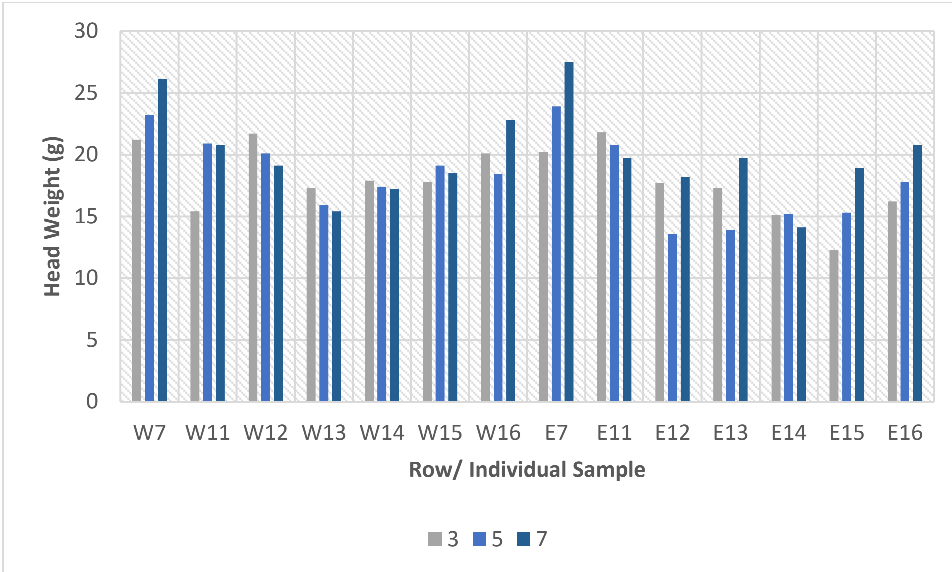


Figure 23. Dry lettuce head weight for 10 samples (1 – 10) from the third experiment for each row number (7 through 16), and each face (East (E) or West (W)). The colors within each group represents the different rows.

Table 5. Total Head and Root Fresh Mass, and Average Head and Root Fresh Mass for 10 plants in the third experiment harvest. Calculations were done in the same fashion as described in table 1.

Fresh Weight	W7	W11	W12	W13	W14	W15	W16	E7	E11	E12	E13	E14	E15	E16
Total Head Mass / Row (g)	4315	3095	3340	2555	2990	2620	2890	3780	3555	2425	2045	1865	1790	2585
Total Root Mass (g)	567	451	620	320	411	310	500	461	435	326	455	330	328	533
Average Head Mass (g)	432	310	334	256	299	262	289	378	356	243	205	187	179	259
Average Root Mass per Head (g)	56.7	45.1	32.6	32.0	41.1	31.0	26.3	46.1	43.5	32.6	23.9	33.0	32.8	28.1
Root Mass Percentage	13%	15%	10%	13%	14%	12%	9%	12%	12%	13%	12%	18%	18%	11%

Table 6. Total Head and Root Dry Mass, and Average Head and Root Dry Mass for 10 plants in the third experiment harvest. Calculations were done in the same fashion as described in table 1

Dry Weight	W7	W11	W12	W13	W14	W15	W16	E7	E11	E12	E13	E14	E15	E16
Total Head Mass / Row (g)	70.5	57.1	60.9	48.6	52.5	55.4	61.3	71.6	62.3	49.5	50.9	44.4	46.5	54.8
Total Root Mass (g)	34.7	29.3	41.1	25.9	31.9	28.8	34.3	31.9	26.9	26.2	54.1	33.2	26.9	34
Avg. Head Mass (g)	24	19	20	16	18	18	20	24	21	17	17	15	16	18
Average Root Mass per Head (g)	3.5	2.9	2.2	2.6	3.2	2.9	1.8	3.2	2.7	2.6	2.8	3.3	2.7	1.8
Root Mass Percentage	15%	15%	11%	16%	18%	16%	9%	13%	13%	16%	17%	22%	17%	10%

Fourth Experiment

The fourth experiment was planted at the highest density (87 Heads m-2) and it was performed to test for any detriment to growth that would occur from running the system at full capacity. The East face was planted 100% filled with 19 plants per row for rows two through six while the West face was planted at 50% or 10 plants per row for rows two through six. The 50% occupancy was accomplished by planting every other hole along each row with the remaining holes left empty.

This highest density planting yielded no differences among plants rows on either east or west face. This experiment required that the bypass valve divert water back to the nutrient reservoir and to reduce the total output from the pump and the flow rate to each row, which provided a reasonable flow and level of water within the row tube, and prevented spill-over from the root mass blocking nutrient solution flow along the tube. The bypass valve was first opened to 25% reduction of flow on the fourteenth day after transplant, and was further opened to 40% on the 22nd and another 10% again on the 28th day, ending one-half closed by the day of harvest.

Due to a reduction in incoming sunlight due to the Winter months, the plants in the fourth experiment grew at a slower rate, requiring nearly the same time period to reach an acceptable market weight of 150 grams that the third trial required to reach fresh weights over 300 grams. This slower growth rate was attributed to the environmental conditions, incoming solar radiation, and not to the spacing arrangement. Figure 24 graphically displays the fresh weights of the heads in the fourth experiment with a standard deviation among means of 22 grams, among the 150 heads that were grown in the arrangement patterns. Tables 7 and 8 were the fresh and dry weight of the fourth experiment harvest. The ANOVA determined that the fresh head mass means were equal throughout the system, and that the high or low density spacing pattern did not affect growth. The ANOVA results of the fresh weight can be seen in figure 25. The p-value of 0.097 for the spacing treatment is above the benchmark of .05 and therefore the null hypothesis of equal means cannot be rejected and the ability of plants to grow in either special arrangement is confirmed. The fourth trial also confirmed that the face which plants were grown on caused no difference in growth, with a p value of .064, indicating no significant effect. The ANOVA for head dry weight is shown in figure 26, and indicates the same as the fresh weight.

Table 7. Total Head and Root Dry Mass, and Average Head and Root fresh Mass for 10 plants in the fourth experiment harvest. Calculations were done in the same fashion as described in table 1

Fresh Weight	W2	W3	W4	W5	W6	W8	W9	W10	E2	E3	E4	E5	E6	E8	E9	E10
Total Head Mass / Row (g)	1675	2165	1995	2125	1515	2040	2025	1695	2045	2205	1825	2135	2180	2300	2665	1625
Total Root Mass (g)	115.0	300.0	275.0	300.0	180.0	415.0	365.0	235.0	325.0	405.0	300.0	245.0	600.0	300.0	330.0	280.0
Avg. Head Mass (g)	167.5	216.5	199.5	212.5	151.5	204	202.5	169.5	204.5	220.5	182.5	213.5	218	230	266.5	162.5
Average Root Mass per Head (g)	11.50	30.00	27.50	30.00	18.00	21.84	19.21	12.37	17.11	21.32	15.79	12.89	31.58	30.00	33.00	28.00
Root Mass Percentage	7%	14%	14%	14%	12%	11%	9%	7%	8%	10%	9%	6%	14%	13%	12%	17%

Table 8. Total Head and Root Dry Mass, and Average Head and Root Dry Mass for 10 plants in the fourth experiment harvest. Calculations were done in the same fashion as described in table 1

Dry Weight	W2	W3	W4	W5	W6	W8	W9	W10	E2	E3	E4	E5	E6	E8	E9	E10
Total Head Mass / Row (g)	48.77	56.42	50.36	53.88	50.21	58.04	59.71	54.23	53.28	53.06	51.9	53.87	58.09	60.59	61.36	50.87
Total Root Mass (g)	11.2	22.2	17.6	17.9	14.0	25.2	23.1	17.9	19.5	22.7	19.8	14.5	21.4	18.2	20.6	18.3
Avg. Head Mass (g)	16.26	18.81	16.79	17.96	16.74	19.35	19.9	18.08	17.76	17.69	17.3	17.96	19.36	20.2	20.45	16.957
Average Root Mass per Head (g)	1.12	2.22	1.76	1.79	1.40	1.33	1.22	0.94	1.03	1.19	1.04	0.77	1.13	1.82	2.06	1.83
Root Mass Percentage	7%	12%	10%	10%	8%	7%	6%	5%	6%	7%	6%	4%	6%	9%	10%	11%

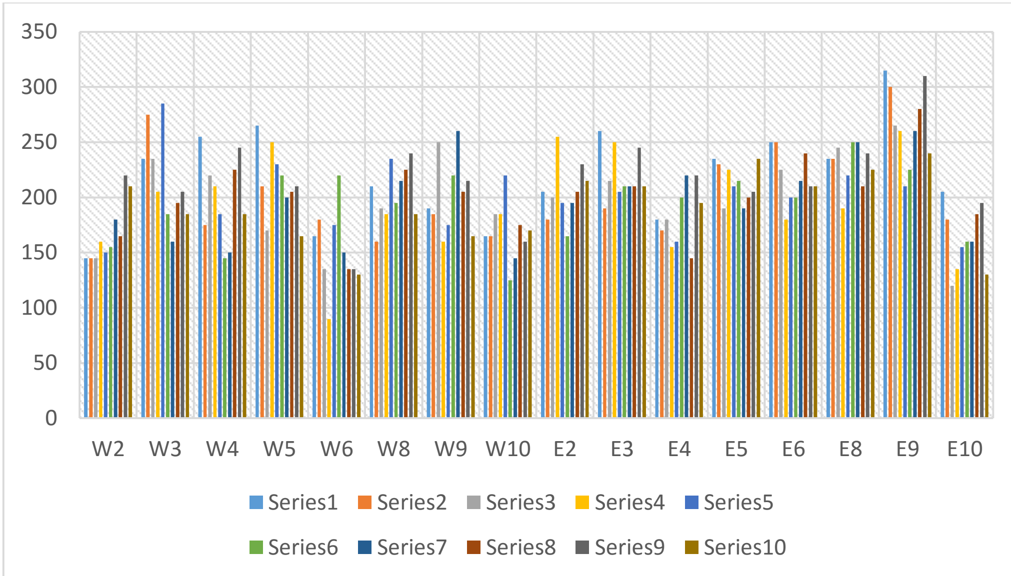


Figure 24. Fresh lettuce head weight for 10 samples (1 – 10) from the fourth experiment for each row number (2 through 10), and each face (East (E) or West (W)).The colors within each grouping represents the different rows.

The ANOVA Procedure
Dependent Variable: Fresh_Weight

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	55111.4583	7873.0655	10.38	<.0001
Error	112	84983.3333	758.7798		
Corrected Total	119	140094.7917			

R-Square	Coeff Var	Root MSE	Fresh_Weight Mean
0.393387	13.50568	27.54596	203.9583

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Row	5	50326.04167	10065.20833	13.26	<.0001
Spacing	1	2125.20833	2125.20833	2.80	0.0970
Face	1	2660.20833	2660.20833	3.51	0.0638

Figure 25. The ANOVA output of the SAS software comparing equal means among spacing arrangements, fresh weight.

The ANOVA Procedure
Dependent Variable: Dry_Weight

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	52.4052778	7.4864683	3.64	0.0065
Error	28	57.6511111	2.0589683		
Corrected Total	35	110.0563889			

R-Square	Coeff Var	Root MSE	Dry_Weight Mean
0.476168	7.785498	1.434911	18.43056

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Row	5	47.56472222	9.51294444	4.62	0.0034
Spacing	1	2.00694444	2.00694444	0.97	0.3320
Face	1	2.83361111	2.83361111	1.38	0.2506

Figure 26. The ANOVA output of the SAS software comparing equal means among spacing arrangements, dry weight.

The four experiments provided the expected production outputs under optimal conditions. The operational inputs included the electrical consumption of the circulation pump, which running continuously, was 5.5 kWh day^{-1}, or 154 kWh for a 28-day production period.

Nutrient solution consumption was approximately 4 liters per head of lettuce over the total growth period, and was an average 3.6, 4.2, and 4.4 l min^{-1} for the second, third and fourth experiments, respectively

The harvest rate of the lettuce heads were estimated to be 95% for each of the second, third and fourth experiments.

Economic Model

The feasibility model for a hypothetical urban agriculture operation was created to allow simple inputs to feed into pre-determined formulas which give the user a clear output of costs and profit from the site. The basis for the model is the validated a-frame hydroponic system discussed above which defines how the grow space inputted by the user will be utilized and from this determination, provides an exact production model that can be adapted to multiple cities and locations.

As the model was being developed, the largest constraint became clarity. To preserve the simplicity of the 'main' sheet, auxiliary sheets were added to the model to perform and explain to the user the calculations that ultimately feed into the cost analysis for the operation. The auxiliary sheets serve two functions, the first is to provide justification for all outputs on the main page and the second being to allow for greater customization and less forced assumptions as can be seen in similar greenhouse pricing models (Donnell, et al., 2011). The customization gives users experienced in the field the ability to decide the exact inputs into the model on every level while still giving the less experienced user the ability to use widely accepted assumptions in the industry to give an accurate prediction of feasibility for a certain area. Nearly all cell formulas feed from other cells, there are few unexplained numbers within the sheet that may skew financial predictions when the user does not know to change them, the only exception being some division by the number of months in a year and certain item pricing. The 'assumptions of the system' portion was added to the main sheet to give the user more clarification on the source of values used later in calculations. The assumptions include the correction multipliers for over-seeding and spoilage prediction, with values of 1.05 and .90, respectively. These multipliers create a conservative outlook of production and give more credence to the production numbers being representative of a real-world facility.

The most difficult input item for any potential user will be the heating cost auxiliary sheet, considering the weather data required. Although this weather data is often easily available to any user through federal and state-run weather reporting programs, it could be streamlined for future use through real-time incorporation of a weather service data system. Many of the other inputs are easily available to all consumers and require minimal effort beyond entering the pricing or rate value into the ‘input’ section of the main sheet. The ‘A-frame build cost’ and ‘nutrient solution calculator’ auxiliary sheets are an accurate representation of current pricing but may require adjustment in the future.

A benefit of this feasibility model is its basis upon ‘cycles’ as the base unit of time. Similar financial budget models often rely on standard dates, either quarterly, monthly, or yearly, however, this time scale does not accurately represent the cash flow of a system utilizing the a-frame hydroponic design. The cycle system is determined by the user as the maximum number of rotations that an individual a-frame system can grow a crop in a 365 day period. Due to varying weather and complexity of acquiring accurate temperature and solar data for any given area, using a growth model would be far too difficult for the average user. It would also be unnecessary for the advanced grower who has the ability to determine number of crop cycles for their given area already.

The goal of the research is the output given in the cost breakdown. The use of cycles as the time determinant allows the user to see their costs of operation both on a per crop basis and a per year basis. The number of years observed is an input by the user which determines total number of cycles for which the system will be in use before replacement of the hydroponic a-frames. The total number of cycles, which is a combination of cycles per year and number of years observed, feeds into the model to determine the rate at which capital expenses such as greenhouse construction costs and the hydroponic system construction costs will be paid off.

A 'year 1 analysis' was added to the main sheet of the calculator to provide the user with a complete perspective on cash flow of the operation. The analysis delves into all of the associated costs and returns of the operation, while proportioning each on a per head, m^2, system, and whole operation basis. This approach can be used to identify strengths and weaknesses of a current pricing plan and give the user greater detail of their operation.

Figure 27 is an example of inputs to the system of a standard commercial greenhouse, from these inputs, the feasibility model then uses the calculations of auxiliary sheets, formulas within the main sheet, and assumptions of the system to model the situation. The facility designations and crop sections are shown in figure 28 with outputs based upon the assumptions of the system which were determined from the crop trials and empirical data. From these determinations, the cost breakdown is formed, giving the user a view of both variable and fixed costs, displayed in figure 29. The model then computes the revenues based upon maximum number of heads which may be grown in the allotted space and the market price for a head of lettuce. The cost analysis is the final output of the model, giving a value for return on investment for the current situation while also outlining the source of costs and returns in the year 1 analysis, as shown in figure 30.

A sensitivity analysis was added to the feasibility model to further the power of the model to predict the financial outcome of a specific urban agriculture operation. The sensitivity analysis functions through the interpolation of two chosen inputs, in this case, growing space and the market price of a head of lettuce. Figure 31 provides the sensitivity analysis from the situation described above and shows the price point, >$2.00 per head of lettuce, where no matter the size of the operation, any price below will not be profitable. The price per head of lettuce is stated along the x axis while the square meterage of the growing operation is listed along the y axis, this sensitivity table is adaptable within the model document to allow the user to see a wide range of pricing and size options and where, according to all other inputs held constant, they may expect to produce a profit. The sensitivity analysis can be done on both a per crop and per year basis with the ability to raise or lower the bounds of either parameter to any desired level.

Figure 27. The input area of the main sheet of the feasibility model. Sixteen input points allow the user to form an accurate model of a hypothetical urban agriculture operation.

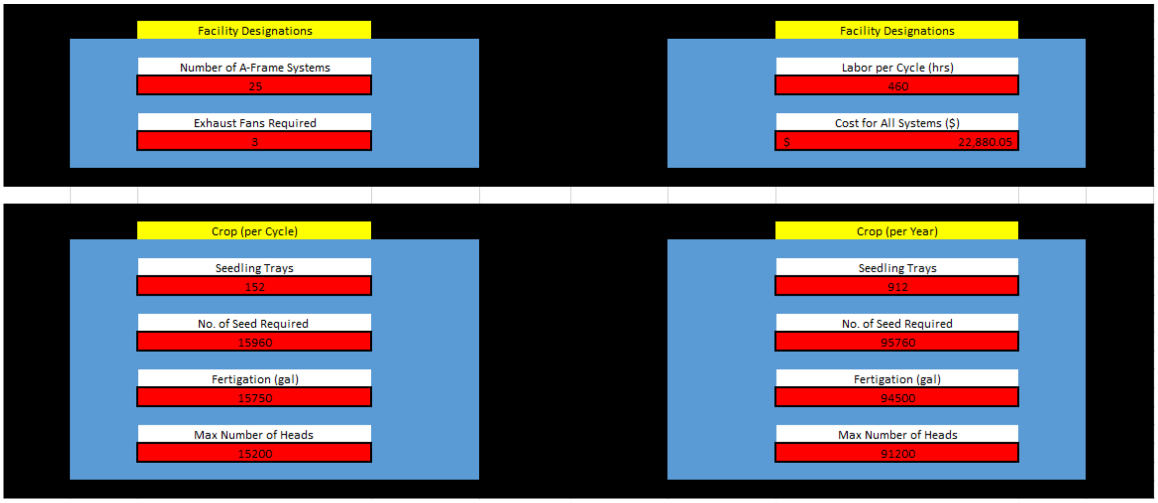


Figure 28. The facility designations area outlines the basic functions calculated from the input area which feed later into the model. The crop section, both in cycle and per year, give the user a clear readout of capabilities of the hypothetical facility.

Cost Breakdown

Variable Costs	Item	Number of Units Required per Cycle	Cost/Unit		Cost per Cycle ($)	Cost per Year ($)
	Seed	15960	$ 0.02	($/seed)	$ 319.20	$ 1,915.20
	Trays	152	$ 4.00	($/Tray)	$ 608.00	$ 3,648.00
	Nutrient Solution	15750	$ 0.0109	($/gallon)	$ 172.22	$ 1,033.29
	Labor	460	$ 8.00	($/hr)	$ 3,680.43	$ 22,082.56
	Heating	118790400	$ 0.48	($/100000 BTU)	$ 570.19	$ 3,421.16
	Electrical/Cooling	3475.56	$ 0.12	($/kw-hr)	$ 417.07	$ 2,502.40
	Additional Materials				$ 86.00	$ 516.00
				Total	$ 5,853.10	$ 35,118.62

Fixed Costs	Item	Quantity	Cost/Unit		Cost per Cycle ($)	Cost per Year ($)
	Land Rental	200	$ 50.00	($/m^2)	$ 20,000.00	$ 120,000.00
	Greenhouse Construction	200	$ 200.00	($/m^2)	$ 833.33	$ 5,000.00
	A-Frame Construction/Materials	25	$ 915.20	($/System)	$ 476.67	$ 2,860.01
	Re-usable Packaging Crates	25	$ 15.00	($/Crate)	$ 7.81	$ 46.88
	Scale	3	$ 100.00	($/Scale)	$ 5.21	$ 31.25
				Total	$ 21,323.02	$ 127,938.13
				All Costs	$ 27,176.13	$ 163,056.75

Figure 29. Cost analysis calculations of the feasibility model under a hypothetical situation models both variable and fixed costs of an operation.

Revenues						
			Price Point		Revenue per Cycle ($)	Revenue per Year ($)
	150-200 (g) Head of Lettuce	15200	$ 2.50	($/Head)	$ 38,000.00	$ 228,000.00
Return on Investment					Profit per Cycle ($)	Profit per Year ($)
					$5,937.54	$35,625.25

Year 1 Analysis					
	Variable Costs ($)	Fixed Costs($)	Total Costs($)	Return Over Variable Costs ($)	Return on Investment ($)
Per Head	$ 0.71	$ 1.40	$ 2.11	$ 1.79	$ 0.39
Per m^2	$ 322.18	$ 639.69	$ 961.87	$ 817.82	$ 178.13
Per System	$ 2,577.46	$ 5,117.53	$ 7,694.99	$ 6,542.54	$ 1,425.01
Per Operation	$ 64,436.62	$ 127,938.13	$ 192,374.75	$ 163,563.38	$ 35,625.25

Figure 30. The revenues, profit and year 1 analysis portions of the feasibility model give the user an area to adjust the market price of a head of lettuce to find an appropriate profit margin. The year 1 analysis gives a breakdown of profit and cost areas within the operation on a per unit basis.

Sensitivity Analysis	(Price vs Growing space (m^2))								
$10,823.87	$ 1.00	$ 1.25	$ 1.50	$ 1.75	$ 2.00	$ 2.25	$ 2.50	$ 2.75	$ 3.00
100	$ (5,993.06)	$ (4,093.06)	$ (2,193.06)	$ (293.06)	$ 1,606.94	$ 3,506.94	$ 5,406.94	$ 7,306.94	$ 9,206.94
110	$ (6,591.37)	$ (4,501.37)	$ (2,411.37)	$ (321.37)	$ 1,768.63	$ 3,858.63	$ 5,948.63	$ 8,038.63	$ 10,128.63
120	$ (7,189.68)	$ (4,909.68)	$ (2,629.68)	$ (349.68)	$ 1,930.32	$ 4,210.32	$ 6,490.32	$ 8,770.32	$ 11,050.32
130	$ (7,787.98)	$ (5,317.98)	$ (2,847.98)	$ (377.98)	$ 2,092.02	$ 4,562.02	$ 7,032.02	$ 9,502.02	$ 11,972.02
140	$ (8,386.29)	$ (5,726.29)	$ (3,066.29)	$ (406.29)	$ 2,253.71	$ 4,913.71	$ 7,573.71	$ 10,233.71	$ 12,893.71
150	$ (8,984.59)	$ (6,134.59)	$ (3,284.59)	$ (434.59)	$ 2,415.41	$ 5,265.41	$ 8,115.41	$ 10,965.41	$ 13,815.41
160	$ (9,582.90)	$ (6,542.90)	$ (3,502.90)	$ (462.90)	$ 2,577.10	$ 5,617.10	$ 8,657.10	$ 11,697.10	$ 14,737.10
170	$ (10,181.21)	$ (6,951.21)	$ (3,721.21)	$ (491.21)	$ 2,738.79	$ 5,968.79	$ 9,198.79	$ 12,428.79	$ 15,658.79
180	$ (10,779.51)	$ (7,359.51)	$ (3,939.51)	$ (519.51)	$ 2,900.49	$ 6,320.49	$ 9,740.49	$ 13,160.49	$ 16,580.49
190	$ (11,377.82)	$ (7,767.82)	$ (4,157.82)	$ (547.82)	$ 3,062.18	$ 6,672.18	$ 10,282.18	$ 13,892.18	$ 17,502.18
200	$ (11,976.13)	$ (8,176.13)	$ (4,376.13)	$ (576.13)	$ 3,223.87	$ 7,023.87	$ 10,823.87	$ 14,623.87	$ 18,423.87

Figure 31. The sensitivity analysis of the feasibility model for a hypothetical urban agriculture operation. Allows better perspective to the user for determining growing space and price point as the two major influencers of profit.

Future research could be incorporated into the feasibility model to improve upon certain features which are either based upon assumption or standard industry practices. The heating cost calculator operates under the principle of user-inputted weather values for their specific area for one year. At the current generation, the model assumes a standard yearly climate for the total number of years observed. Future models could incorporate real time weather inputs from governmental or research institution weather collection services and could feed these values into the heating cost calculations. The ability to compare different hydroponic system styles, such as deep water culture versus nutrient film technique, would be another point of improvement for the model. Comparison of other hydroponic systems is beyond the goals of this research, so it was not included but it could be done through alteration of system assumptions and certain cost factors. Investors may also be interested in partitioning crop sales between wholesale and premium market pricing, however, this is beyond the scope of this research and would involve major changes to the cost breakdown sector.

CONCLUSION

The economic model is adaptable to a wide array of locations due to the flexibility afforded by auxiliary sheets. The use of auxiliary sheets improved clarity and customization for the user. A net profit was determined by use of the model for a market price of $2.00 per head of lettuce when incorporating inputs from realistic scenario greenhouses, and empirical and commercial data. . The economic model delivered a preliminary view of an urban agriculture operation providing investors information about the viability of a proposed business venture.

The hydroponic design performed well, and exceeded previous NFT A-frame designs in the number of heads per system within a given footprint (Kacheris, 2014). The low weight of the system from the small reservoir and aluminum structure were well suited for a rooftop in addition to its effective use of three dimensional space for crop production. The high density spacing of 79.5 heads m^{-2} provided a uniform and quality harvest. The multiple trials performed with the system confirmed plant production uniformity and the ability to use the system as a basis for the output area of the economic model, and not having to use unreliable empirical data. This will provide a grower the ability to utilize this system and have confidence in economic predictions.

References

Aldrich, R.A. and Bartok, J.W., 1994. Greenhouse engineering. *NRAES (USA)*.

Bakker, N., Dubbeling, M., Gündel, S.A.B.I.N.E., Sabel Koschella, U. and Zeeuw, H.D., 2000. *Growing cities, growing food: urban agriculture on the policy agenda. A reader on urban agriculture*. DSE.

Barbosa, G.L., Gadelha, F.D.A., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., Wohlleb, G.M. and Halden, R.U., 2015. Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic vs. Conventional Agricultural Methods. *International journal of environmental research and public health*, *12*(6), pp.6879-6891.

Barham, J., Tropp, D., Enterline, K., Farbman, J., Fisk, J. and Kiraly, S., 2012. *Regional food hub resource guide* (No. 145227).

Brechner, M., Both, A.J. and Staff, C.E.A., Hydroponic Lettuce Handbook.*Cornell Controlled Environment Agriculture*.

Chan, K.W., 2007. Misconceptions and complexities in the study of China's cities: Definitions, statistics, and implications. *Eurasian Geography and Economics, 48*(4), pp.383-412.

Christie, C. B., and M. A. Nichols. "Aeroponics-a production system and research tool." *South Pacific Soilless Culture Conference-SPSCC 648*. 2003.

Donnell, M., Short, T., Moore, R. and Draper, C., 2011. Hydroponic Greenhouse Lettuce Enterprise Budget. *Columbus, OH*.

Drechsel, P. and Kunze, D. eds., 2001. *Waste composting for urban and peri-urban agriculture: Closing the rural-urban nutrient cycle in sub-Saharan Africa*. CABI.

Food Marketing Institute. 2011. *U.S. Grocery Shopper Trends*, Food Marketing Institute: Arlington, VA.

Getter, K.L. and Rowe, D.B., 2006. The role of extensive green roofs in sustainable development. *HortScience*, *41*(5), pp.1276-1285.

Graves, C.J., 1983. The nutrient film technique. *Horticultural Reviews, Volume 5*, pp.1-44.

Giacomelli, G.A., 2002, July. Considerations for energy management of greenhouse heating and cooling. In *Southern Greenhouse Vegetable Growers Association Conference*.

Gumble, J., Berghage, R. and Stearns, D., 2015. Production and Financial Analyses of the Rotating Living Wall, an Urban Agricultural System. *Journal of Environmental Protection*, *6*(9), p.1029.

Hendrickson, M.K. and Porth, M., 2012. Urban Agriculture—Best Practices and Possibilities. *University of Missouri*, pp.1-52.

Hoagland, D.R. and Arnon, D.I., 1950. The water-culture method for growing plants without soil. *Circular. California Agricultural Experiment Station*, *347*(2nd edit).
Jensen, M.H. and Collins, W.L., 1985. Hydroponic vegetable production. *Horticultural Reviews, Volume 7*, pp.483-558.

Kacheris, W. 2014. Evaluation of Capacity: A Novel 3D Hydroponic System Design. University of Florida.

King, R.P., 2010. *Comparing the structure, size, and performance of local and mainstream food supply chains* (Vol. 99). DIANE Publishing.

Kozak, A.E., 2015. *Envisioning a self-sustaining city: The practice and paradigm of urban farming in Shanghai*. University of Colorado at Denver.

Kujawski, R. and Ryan, D. 2014. Fertilizing Trees and Shrubs. *UMass Extension, Landscape, Nursery and Urban Forestry Program*.

University of Guelph. University School of Rural Planning and Development and Leinan, V.A., 2002. *Sustainable Livelihoods and the Role of Urban Agriculture as a Policy and Household Strategy in Cienfuegos, Cuba*. University of Guelph.

Leisinger, K.M., Schmitt, C. and Pandya, L., 2002. Six Billion and Counting: Population and Food Security in the 21st Century (Washington, DC: International Food Policy Research Institute, 2002). *I am indebted to Todd Benson, an old friend and staff member at the International Food Policy Research Institute, for better understanding issues related to food security in sub-Saharan Africa*, pp.4-6.

Licamele, J.D., 2009. Biomass production and nutrient dynamics in an aquaponics system.

Lichter, D.T. and Brown, D.L., 2011. Rural America in an urban society: Changing spatial and social boundaries. *Annual Review of Sociology*, *37*, pp.565-592.

Low, S.A., Adalja, A., Beaulieu, E., Key, N., Martinez, S., Melton, A., Perez, A., Ralston, K., Stewart, H., Suttles, S. and Vogel, S., 2015. Trends in US local and regional food systems. *US Department of Agriculture, Economic Research Service. Washington, DC.*

Luxhoj, J.T. and Giacomelli, G.A., 1990. Comparison of labour standards for a greenhouse tomato production system: a case study. *International Journal of Operations & Production Management*, *10*(3), pp.38-49.

Magigi, W., 2013. Urbanization and Its Impacts to Food Systems and Environmental Sustainability in Urban Space: Evidence from Urban Agriculture Livelihoods in Dar es Salaam, Tanzania. *Journal of Environmental Protection*, *4*(10), p.1137.

Mendes, W., Balmer, K., Kaethler, T. and Rhoads, A., 2008. Using land inventories to plan for urban agriculture: experiences from Portland and Vancouver. *Journal of the American Planning Association*, *74*(4), pp.435-449.

Mougeot, L.J., 2000. Urban agriculture: definition, presence, potentials and risks. *Growing cities, growing food: Urban agriculture on the policy agenda*, pp.1-42.

Neuner, K., Kelly, S. and Raja, S., 2011. Planning to Eat? Innovative Local Government Plans and Policies to Build Healthy Food Systems in the United States.

Novo, M.G. and Murphy, C., 2000. Urban agriculture in the city of Havana: A popular response to a crisis. *Growing cities, growing food. Urban agriculture on the policy agenda. (ZEL)*, pp.329-346.

Un-Habitat, 2008. *State of the World's Cities 2008-2009: Harmonious Cities*. Earthscan.

Sanyé-Mengual, E., Cerón-Palma, I., Oliver-Solà, J., Montero, J.I. and Rieradevall, J., 2013. Environmental analysis of the logistics of agricultural products from roof top greenhouses in Mediterranean urban areas. *Journal of the Science of Food and Agriculture*, *93*(1), pp.100-109.

Sheikh, B. A. "Hydroponics: key to sustain agriculture in water stressed and urban environment." (2006): 53-57.

Soares, H.R., Silva, Ê.F.D.F., Silva, G.F.D., Pedrosa, E.M., Rolim, M.M. and Santos, A.N., 2015. Lettuce growth and water consumption in NFT hydroponic system using brackish water. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *19*(7), pp.636-642.

Kristina, H.T., 2001. Organic status and dietary role of organoponicos in Cienfuegos.

Yi-Zhang, C. and Zhangen, Z., 2000. Shanghai: trends towards specialised and capital-intensive urban agriculture. *Growing cities, growing food, urban agriculture on the policy agenda*, pp.467-76.

Appendix

Appendix i: Jensen Hydroponic lettuce formulation:

	N	P	K	Ca	Mg	S	Cl
	RECOMMENDED LETTUCE NUTRIENT SOLUTION (CEAC)						
TANK 1	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Cl**
Ca(NO3)2	134			165			
CaCl2.6H20				35			60
TANK 2							
KNO3	46		137				
KH2PO4		50	61				
MgSO4.7H20					40	52	
TOTAL PPM	**180**	**50**	**198**	**200**	**40**	**52**	**60**

	RECOMMENDED COMPOUNDS IN NUTRIENT SOLUTION		
TANK 1	**Kg.**	**TANK 2**	**Kg.**
Ca(NO3)2	8.2	KNO3	3.4
CaCl2.6H20	1.8	KH2PO4	2
		MgSO4.7H20	3.8
TOTAL SALTS	**10**	**TOTAL SALT**	**9.2**
Assumptions:			
Stock solution tanks - 25 gal. each (95 liters) Fert. Injector Ratio = 100:1			

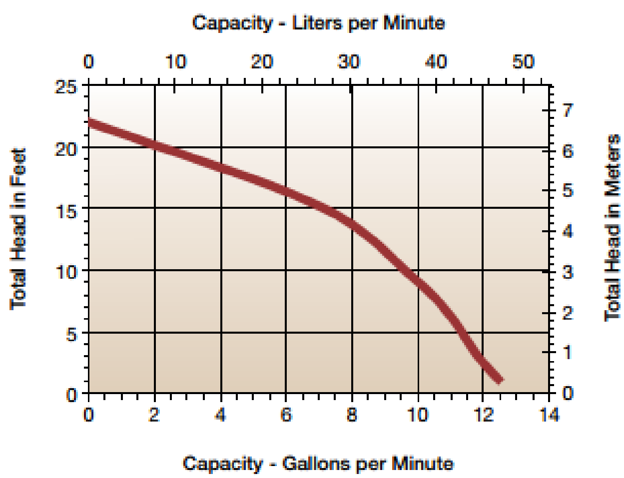
Appendix ii: A-Frame Construction Build List:

10' A-Frame Construction	
Item	**Section**
2", Square Dr Screws (50/Box)	Structure
Conduit U-Clamps(4 pack)	Structure
1.5"x20' PVC Pipe	Grow Channels
.75" x 20' PVC Pipe	Manifold
.50" x 20' PVC Pipe	Manifold
6-Way Rainbird Splitter	Manifold
Roll of Drip Tubing x 50'	Manifold
90 bend .5" elbow Slip x Thread	Manifold
Tee .5" Slip x Thread x Slip	Manifold
Extender .5" Threaded	Manifold
Adapter .5" Slip x Thread	Manifold
Adapter .5" Thread x Nipple	Manifold
Poly Flex Tubing x 2'	Manifold
Elbow .5" Thread x Nipple	Manifold
Tee .5" Thread x Thread x Thread	Manifold
Bushing .5" Thread x 1.5" Slip	Manifold
Coupling 1.5" Slip x Slip	Manifold
Bushing 1.5" Slip x .75" Thread	Manifold
Inline y Filter .75" Thread x Thread	Manifold
Union/Valve .75" Slip x Slip	Manifold
Adapter .75" Thread x Slip	Manifold
Bulkhead .75" Thread	Manifold
Centrifugal Pump, 1/12 HP	Manifold
End Caps 1.5" Slip	Manifold
Sanitary Tee 1.5" Slip x Slip x Slip	Return
45 Bend 1.5" Slip x Slip	Return
90 Bend Elbow 1.5" Slip x Slip	Return
Tee 1.5" Slip x Slip x Slip	Return
Union 1.5" Slip x Slip	Return
Adapter 1.5" Slip x 1" Thread	Return
Bulkhead 1" Thread	Return
Reservoir 110 Gal Farm Tank	Reservoir
Styrofoam Covers	Reservor
Aluminum Angle Struts x 18'	Structure
5/8" Bolt Assembly	Structure
Teflon Tape, Roll	Miscellaneous
PVC Cement/Primer, 8 oz	Miscellaneous
Hose Clamps x 10	Miscellaneous

Appendix iii: Pump Sizing Calculation:

	Pump Sizing		
	l/Min/Trough	# of Troughs	Total Flow(l/min)
Standard (1 liter/min)	1	32	32.0
High Flow System (2 liter/min)	2	32	64.0
Medium Flow System (1.5 liter/min)	1.5	32	48.0

	Dynamic Head		
	"K" Factor	Quantity	Meter Head/Section
Main Vertical 1.5" Pipe	1.01	6	1.8483
90° Elbow 1.5"	0.75	2	0.4575
Tee (All 1.5")	1	1	0.305
5/8" Tubing	0.1377	10	0.419985
1/4" Drip lines	0.0268	32	0.261568
		Total Head (m)	3.29



This was calculated using $h=k(V^2/2g)$, with a calculated vel. of 1.5 ft/s.