STUDY OF THE SUSTAINABILITY ISSUES OF FOOD PRODUCTION USING VERTICAL FARM METHODS IN AN URBAN ENVIRONMENT WITHIN THE STATE OF INDIANA

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Dedicado a mis padres, porque siempre han tenido fe en mí.

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ABSTRACT

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There are several problems around the globe related to water scarcity, energy shortages, deforestation and loss of fertile land, and food security. Climate change is making environmental and social issues arise. Issues such as, changes in the agricultural landscape, increasing population (9 billion is the expected population for 2040), rising food borne illnesses, scarcity of drinking water, and more crop failure due to plant pathogens and insect pests, among other factors make this study specially significant. Vertical farming could be a potencial solution to some of these problems.

Due to these problems the present thesis analyzed vertical farming as a possible solution for the future of food production. The study has used lettuce as an example of what vertical farming could offer. The analysis was focused on the productivity of the vertical farm, the location within the state of Indiana, the water used, the carbon footprint, and the energy needed to run the vertical farm with 100% supplemental LEDs.

The analysis of the data was done using ArcGIS software, and data from the Indianamap website, to create a model that was able to determine the most suitable

locations within the State of Indiana. Once the location was determined the author estimated the amount of electrical energy needed to grow lettuce indoors, using LEDs. As well as the energy analysis, the author focused on the water footprint and carbon footprint of the hypothetical vertical farm.

The findings of this thesis are both encouraging and discouraging but they also form a starting point for further research. These results are based on the assumptions, limitations and delimitations of this study. The most suitable locations in the State of Indiana to locate a vertical farm, under the parameters used, are Anderson, Brazil, Columbia city, Connersville, Gary, Mishawaka, and Terre Haute. The use of energy just for lighting is around 133million kWh, which is the equivalent to 12,326 American households of four during a year, the water footprint is 33 times less than conventional crops, which is around 237l H_2O/kg of lettuce produced. Although the purpose of this thesis was not to generate a comparison of vertical farm to conventional open field agriculture, important data that could form the foundation for such comparison were generated. These data include the carbon footprint that is 56,258 tones of CO_2 per year, which are the emissions made by approximate 3,200 Americans during a year, and the productivity of this vertical farm of 10 story vertical farm and dimensions of 100mx100m with stacked drums would be around 8,482 tones of lettuce /year, enough to satisfy the daily needs of fresh vegetables of more than 100,000 people if only were eating lettuce.

Some of the recommendations for further research are to include social implications into the analysis, as well as a cost benefit economic analysis of vertical farming methods versus conventional open field to determine the economical feasibility of vertical farms, as well as a detailed comparison of methods between vertical farming and conventional farming.

RESUMEN

El presente trabajo de final de master analiza la posibilidad de usar tecnología de "*vertical farming*" como sustituta de la producción convencional de lechuga en campo abierto, en el estado de Indiana, Estados Unidos. El concepto "*vertical farming*" es interpretado por el autor de la tesis como entornos con ambiente controlado mediante tecnología. Los factores que entran en juego son: la ventilación, deshumidificadores, control de riego y nutrientes, iluminación, y control de calidad entre otros. En esta tesis, el autor ha concentrado el análisis de una hipotética "vertical farm" de dimensiones 100mx100mx10pisos y en el consumo energético derivado del uso de luz artificial en esos pisos, exceptuando el décimo piso, ya que este funcionaría como un invernadero común bajo luz natural.

La tesis se centra en dos pilares fundamentales, el primero es el consumo eléctrico, principalmente por el uso de luz artificial (cuya fuente de luz artificial también es escogida tras el análisis de la literatura) y deshumidificadores. El resto de elementos de control del ambiente quedan excluidos del análisis y por ende también del coste energético. El segundo pilar de la tesis es el consumo de agua que se necesitará para la producción de lechuga.

Para el desarrollo de esos dos puntos ha sido necesario también la determinación del método usado para hacer crecer la cosecha de la especie elegida, en este caso

"*stacked drums*", al igual que el método de iluminación más eficiente, en este caso LEDs.

En el proceso de análisis de la tesis se ha utilizado el software ArcGIS 10.1 para localizar los puntos más óptimos en el estado de Indiana, siguiendo los parámetros descritos en la tesis. Estas localizaciones han sido clasificadas en orden de importancia en los apéndices.

Aunque al margen del objetivo inicial de la tesis, el autor ha incluido en el análisis las emisiones de gases de efecto invernadero equivalentes en CO_2 derivadas de los kWh del consumo eléctrico del complejo.

CHAPTER 1. INTRODUCTION

This thesis studies a new method to provide the food of the future. The future of food production is an interesting question that multiple authors and researchers are examining.

Issues of higher population, less water, an increase in the price of food, and less crude oil all add to a recipe for creating a global food crisis, a crisis for the people and also for the governments.

One fact is that we are a growing population and estimations for 2050 indicate that the population will reach the number of nine billion human beings (Despommier, 2010; BBC, 2009), which means more mouths to feed.

There is also an important economic factor. Some rising economies are creating more wealth and demanding not only more food, but also more varieties of food, and more meat in particular, which needs much more investment in oil and water per kilogram than vegetables.

The case of India is interesting to mention to introduce some of the global problems and complexity surrounding food. The country was self-sufficient, but some years ago India began importing food due to the decline in the yield of crops. This decline was caused by the overexploitation of aquifers, which led to the decline of its agriculture. Water levels in the aquifers increasingly fell so low that the wells of the farmers could no longer reach the water. These farmers, driven by the need to cultivate, had to borrow money to make deeper wells where water is of lower quality and higher in salt content causing a drop in agricultural production, the devastation of which drove many farmers to suicide. The suicide of farmers may not be a common fact around the world, but in India it is happening, and the environmental and agricultural problems that are seen there are occurring all around the globe. (BBC, 2009).

Forecasters predict that in 15 years the decrease of food production will be equivalent to the current entire production in the United States (BBC, 2009). The increase in food imports (by rich countries) is generating a big water footprint in the third world countries.

The rich countries are basically exporting drought conditions when importing products that have the need for a certain amount of water for successful production. For example, the website http://www.waterfootprint.org/?page=files/home managed by the *University of Twente, the Netherlands*, (2011):

A. 1,000 liters of water to produce 1 liter of milk

B. 300 liters of water to produce 1 liter of beer

C. 2,500 liters of water to produce 1 kilogram of rice

D. 1,600 liters of water to produce 1 kilogram of wheat bread

E. 15,000 liters of water to produce 1 kilogram of beef

F. 3,000 liters of water to produce 1 liter of ethanol

These examples are showing the amount of water that takes to produce some of the common daily products that people consume in the daily diet. Europe used about 3,000 liters/person/day of water, in form of food mostly. The author wanted to introduce the concept of virtual water to help build the case and have a broad understanding of the complexity of the problem. Because the water that is embodied in products that are imported is not reflected in the official data of water consumption of the country. When calculating the water footprint is important to take into consideration the virtual water to came up with a more realistic quantity per capita and country.

> International trade in food and other products implies international flows of virtual water. Virtual water is the water that is virtually embedded in traded commodities. It refers to the water footprint of a commodity in the place of production.

The global volume of international virtual water flows in relation to trade in agricultural and industrial products averaged 2320 billion m³ per year during the period 1996-2005 (Mekonnen and Hoekstra, 2011). The major gross virtual water exporters were the USA, China, India, Brazil, Argentina, Canada, Australia, Indonesia, France and Germany and the major gross virtual water importers were the USA, Japan, Germany, China, Italy, Mexico, France, the UK and the Netherlands. The biggest net exporters of virtual water are found in North and South America (the US, Canada, Brazil and Argentina), Southern Asia (India, Pakistan, Indonesia, Thailand) and Australia. The biggest net virtual water importers are North Africa and the Middle East, Mexico, Europe, Japan and South Korea.
For water-scarce countries it can sometimes be attractive to import virtual water (through import of water-intensive products), thus relieving the pressure on the domestic water resources. This happens for example in Mediterranean countries, the Middle East and Mexico. Also Northern European countries import a lot of water in virtual form (more than they export), but this is not driven by water scarcity. International trade patterns can only be understood from a multitude of factors; water scarcity is merely one of them. Hoekstra and Hung (2005) 45-56.

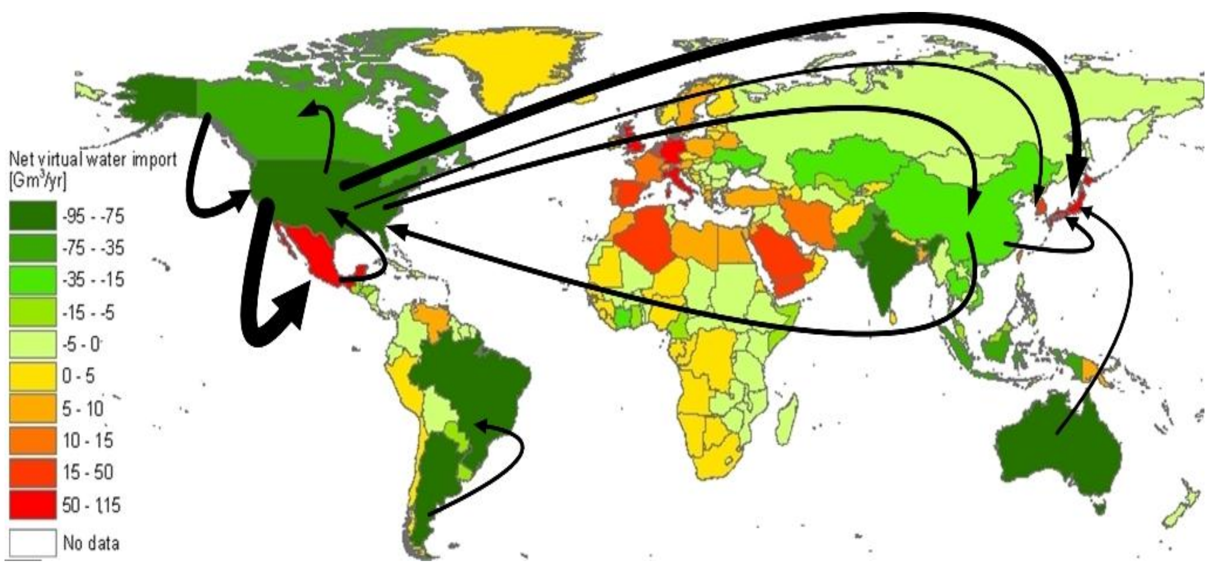

Figure 1.1 Global net virtual water import
M.M. Mekonnen A.Y. Hoekstra. (2011, p.21)

The figure above shows the main movements of virtual water around the world.

There is also a “crude oil thirst”, people use crude oil for the tractors to transport food, to cook, to create fertilizers and pesticides, and for storage, processing and packages. The following are examples of the amount of crude oil it can take to produce many daily products:

1. 70ml oil/ 100g pork chop
2. 140ml oil/ 100g cheese
3. 370ml oil/ 1 tomato grown in a green house

The price per barrel of crude oil fluctuates, decreasing or increasing depending on the year, but its tendency is to increase its price. One fact is for certain, crude oil is not going to last forever as the supply is not inexhaustible. What impact will a lesser amount of crude oil have on the food supply? People cannot know for certain. The author wanted to pay attention to the case of Cuba (Altieri, Companioni, Cañizares, Murphy, Rosset, Bourque, & Nicholls, 1999). Cuba had to switch to a diet that is less fatty and requires much less fuel to produce, a diet that is also healthier. Cuba faced this problem by encouraging its population to grow their own vegetables and fruits. The government also changed the legislation to allow the people to have a surplus amount of products in their gardens so they could sell their goods and gain additional economic benefits.

Cultivating local products typical of the Cuban diet, maximizing production and avoiding monocultures have managed to increase the production of food by 25% using the same amount of land. Cuba changed because they needed to.

What about Europe and the United States? Why should they change? Part of the answer lies in the following question: will they have oil forever? If not, is the actual model of mass food production going to be sustainable?

Another disconcerting issue that negatively affects food production is climate change. In some areas of the world, the effects of climate change are causing losses in agriculture. In India it is estimated that for each degree Celsius that the temperature increases there is a decrease of 5% to 10% of yield production. Other predictions are estimating a loss in the yield of up to 50% by the year 2020 in some countries of Africa. In Kenya, climate change is a reality; the Masai can no longer predict the rain as they had been doing for centuries (BBC, 2009). Also, droughts are four times more common causing the death of a higher number of cows, which means a decrease in cattle availability.

Another issue that prompts a serious look into the future of food production is health and nutrition. Humans live in a world with one billion overweight people, with rates of obesity increasing, and not only due to the amount of food but also the quality of the food. In contrast, there are one billion people going to bed hungry every night. Concerning nutrition, added sugars and salt in processed food is producing health problems such as high blood pressure and an increase of the probability of heart disease. Some people's diets are based on fresh food, but the cost is traditionally higher and not everyone can afford it. Processed products may cost less money at the register, but they have hidden costs. High levels of salt, sugar, modified maize starch, or palm oil (obviously the most cost effective version that one can get) to make the products look good and have a longer shelf life, do not make these products a healthy choice for consumption. That is why it is necessary to start reading the ingredients in the packages of the products that are purchased. (BBC, 2009).

It is necessary then to produce not only enough food but enough of the right kind. Nevertheless other countries are adopting the “food culture” of the Western world.

Another example of unsustainable method of food production, in this case overfishing has been and still is a worldwide problem. The case of the cod fish is a specific example the author exposes in order to make the reader understand that there is a problem related to the availability of natural resources and the actual rhythm of consumption of the human being, and that is not new. According to the book *Ideas and Solutions for a Planet in Crisis* by James Bruges, (2007), the Atlantic waters of New England, in the United States, were the best fishing grounds of codfish in the world. Over one century, these waters have served cod fish to both the United States and Europe. The codfish have a long life cycle and with the introduction of trawl nets the fisherman scooped up all the fish, with no consideration of size or age. The direct consequence was a dramatic decrease in the mature population and its ability to spawn. Fishermen did not realize until mid-1980s that this practice was ending their livelihood in the ocean and also putting an expiration date for their unsustainable but short-term profitable lifestyle. Politicians did nothing to avoid the natural and economic catastrophe that the loss of the cod could have. By 1992, no more codfish were found in the waters of New England. When the cod was gone, the same happened to the jobs of these fishermen as well as tourism.

According to the magazine the *New Internationalist*, February 2007 "The world's fishing industry produces $70 billion worth of fish – so long as stocks last. It receives $54 billion in subsidies" (p.3).

In the Northern Sea in Europe fisherman are now catching only a fraction of what they used to catch, 15 times less than in 1920. The industry is fishing too intensively, and not only are there less fish, but the fish caught are smaller in size, which means they are younger and have not reached their reproductive age. In the XIX century, the average cod was 10kg; now it is around three kilogram to five kilograms. As a result of these shortages, countries such as the UK have started importing fish from countries like Senegal, a country that also has its own food shortages. More than 75 percent of fish stocks are overexploited in the world, and that jeopardizes the billions of people who depend on fish for survival.

Why are countries importing so much food that can be grown within their own country? Imports once were used to complement what each country could not produce, but now it is a competition.

Consumers want everything all year round, and countries such as Kenya or Senegal help to supply the demand; even when their own countries are officially in the middle of a food shortage, they continue to export.

1.1 Problem Statement

There is a worldwide problem with food production. Every year trillions of dollars are lost in crops around the world. Multiple factors affect this issue, from plagues of insects and plant diseases, and more recently, droughts and flooding, extreme temperatures, soil erosion and desertification. Globally, those factors have become more frequent, have been intensified, and take place concurrently because of the effects of climate change and poor management of the natural resources by mankind. Also, a growing population is putting more and more pressure on the natural ecosystem in order to satisfy its growing needs as well. More people mean more mouths to be fed. In a finite world, the population cannot continue to grow indefinitely. The amount of arable land is limited, and even if all the available land on earth were used to increase the food production, other issues would occur including increased erosion, increased use of limited fresh water and wildlife would suffer due to limited space.

The research investigated the concept of 'vertical farming' in order to produce agricultural crops year round in a controlled environment, free of plagues and other stresses that cause the loss of millions in revenue around the globe. Producing food locally in cities, making urban areas a source of production as well as of a source of consumption. This also shortens the chain of distribution, reducing the use of oil.

By producing food in the city and by using less land surface area, the population will be able to stop increasing their use and expansion of land and may even reduce the land used for agricultural purposes, returning some land to its natural state.

In order to be able to survive as a species and protect the natural environment at the same time, the vertical farm is opening a new era of producing food.

1.2 Research Question

This thesis has studied: The feasibility of replacing mass-produced lettuce with locally grown lettuce utilizing Vertical Farm (VF) methods. Other sub questions that will be answered: Where should a Vertical Farm (VF) be built in an urban or suburban environment within the state of Indiana?, What is the relative energy demand of lettuce production in a vertical farm or controlled environment to provide lettuce for the location ‘X’? What is the relative demand for water of lettuce production in a vertical farm or controlled environment to provide lettuce for the location ‘X’? What is the amount of lettuce produced by the hypothetical vertical farm?; What is the carbon footprint of lettuce production relative to the electric consumption (lighting) of the vertical farm?

1.3 Scope

The author has studied different possible paths to answer the research question and the problems cited in the Section 1.2.

There are alternatives to traditional agriculture like urban agriculture. We have some examples in big cities in the Midwest like Chicago where neighborhoods are taking action to grow their own crops. Another example in Cuba, where there is a shortage of vegetables and fruit, people are now being encouraged to grow their own food. With these initiatives more people are becoming attracted to the idea of urban indoor farming, which is the main theme of this study. Many countries and people hope to benefit from vertical farming where one can maximize the efficiency of their harvest.

Some of the ideas that the author covered within the analyses of the vertical farm on the location “X” (that is determined with ArcGIS software in Chapter 3. Methodology and Chapter 4. Data analysis of the thesis) is that could also be a solution of chronic urban problems like physical deterioration of housing, factories, shops, poverty and unemployment, health issues, and environment.

The vertical farm is the balance between engineering and natural sciences with several implications both social and environmental. The study's scope is broad, ranging from the study of the type of lighting used, knowledge of agricultural and biological engineering, the type of plant and under what conditions, and the amount water used in both systems, (Vertical Farm versus conventional open-field farm)

1.4 Significance

The author examined the pressing issues that are occurring in the world and the increasing tendencies on the future.

Some of these effects are listed below: (BBC, 2009).

- Climate change is altering the agricultural landscape
- We are 7 billion mouths to feed, and 9 billion is the expected population for 2040
- Food borne illnesses are on the rise
- Drinking water is becoming scarce in many places
- More crops are failing due to plant pathogens and insect pests
- Half of the population of the world goes to bed hungry every night

Only in the US were estimated $20 billion in crops lost in 2012 due to drought that affected mainly corn, soybeans, wheat and sorghum. More than 215 million tons of potatoes, rice, wheat, corn, and soybeans are destroyed per year due to plant diseases like wheat rust or rice blast.

It is necessary to put the efforts in developing new technologies to feed the population for the XXI century but also people need a change their life style, because it is obvious that population cannot grow indefinitely in a finite world.

1.5 Definitions

Aeroponics - Is the process of growing plants with roots in air or mist environment without the use of soil. The term aeroponic comes from the Greek words *aero* and *ponos* meaning labor air respectively. Aeroponic crops differ from conventional hydroponics and in vitro growth (Rosas, 2007).

Aquaponics - Is the combination of aquaculture and hydroponics. Is the combined culture of fish and plants in recirculating systems. Nutrients generated by the fish, either by direct excretion or microbial breakdown of organic wastes, are absorbed by plants cultured hydroponically. Fish provide most of the nutrients required for plant growth. As the aquaculture effluent flows through the hydroponic component of the recirculating system, fish waste metabolites are removed by nitrification and direct uptake by the plants, thereby treating the water, which flows back to the fish-rearing component for reuse. However, there is a scale problem because the fish produce far more waste than the plants can use when each half is at a reasonable scale. (aquaponicsglobal.com, 2012).

Biomass power - Electricity and biogas obtained through burning and fermentation (respectively) of traditional crops such as corn (the most common) and sorghum agro waste such as peanuts and sunflower, or industrial waste associated with forest exploitation as sawdust. (California Energy Commission, 2014).

Biomimetrics/Biomimicry - The examination of Nature, its models, systems, processes, and elements to emulate or take inspiration from in order to solve human problems. The term biomimicry and biomimetics are derived from the Greek words *bios*, meaning life, and *mimesis*, meaning to imitate. Biomimetics is the study of the structure and function of biological systems as models for the design and engineering of materials and machines (sustainability.about.com, 2014).

Brownfields - Previously used land or to sections of industrial or commercial facilities that are to be upgraded. The land may be contaminated by low concentrations of hazardous waste or pollution, and has the potential to be reused once it is cleaned up (epa.gov, 2011).

EcoMachines - Can be a tank based system traditionally housed within a greenhouse or a combination of exterior constructed wetlands with Aquatic Cells inside of a greenhouse. The system often includes an anaerobic pre-treatment component, flow equalization, aerobic tanks as the primary treatment approach followed by a final polishing step, either utilizing Ecological Fluidized Beds or a small constructed wetland. The result is an efficient and refined wastewater treatment system that is capable of achieving high quality water without the need for hazardous chemicals (Todd, 2012).

Hydroponics - Is the cultivation of plants by placing the roots in liquid nutrient solutions rather than in soil; soilless growth of plants (Tyson, 2012).

Nitrification - Is the process by which ammonia is converted to nitrites (NO_2-) and then nitrates (NO_3-). This process naturally occurs in the environment, where it is carried out by specialized bacteria (Jacob, R., and Cordaro, E., 2000).

Sustainability - The term *sustainable development* has been widely used in scientific, business, and public institutions since it was first defined in the Bruntland Commission's "Our Common Future" in 1987. Sustainable development in that context refers to "*development that meets the needs of the present without compromising the ability of further generations to meet their own needs*." (iisd.org/sd/, 2013; epa.gov/agriculture/tsus.html., 2012)

Urban agriculture - It is the growing of plants and the raising of little animals like fish using aquaponics within and around cities; it is integrated into the urban economic and ecological system: urban agriculture is embedded in -and interacting with- the urban ecosystem (Ruaf foundation, 2013).

Vertical farm - Is the cultivation of plants (crops or not) in different vertical layers to minimize the space use also called controlled environments, plant factories, etc.

Water Footprint - Is the total amount of freshwater used directly and indirectly by consumers and manufacturers. (siemens.com, 2011).

1.6 Assumptions

This analysis will be performed with the collection of data from different geographical locations. The researcher made the following assumptions:

- The cost of electricity does not change with the different location.
- The cost of the water does not change with the different location.
- The production of food is constant and uninterrupted.
- It is assumed that all the produced is purchased by the local consumers.
- The author assumed a 10% as a minimum percentage of loss is added to the

calculation of biomass production per unit of time (daily, weekly, biweekly, monthly or yearly).

- The author has chosen Indiana because of the accessibility of the data with the assumption that this project is replicable to other places (anywhere). Despite that Indiana does not have real problems of availability of horizontal space, or accessibility to water.
- The author has assumed that all the points located in the map of the State of Indiana are equally valid as location for the vertical farm.
- The author has assumed less expensive land and lower construction costs in a peri-urban or suburban environment than in an urban environment.
- When calculating the costs of energy, the cost of distribution and transportation is going to be assumed as zero due to the short distances that the product has to travel.
- The author has assumed that the vertical farm has to be located in a: Brownfield in the State of Indiana, within a county population of more than 100,000 people, with a population density bigger than 100 people for square kilometer. A school, a Hospital and a Composting facility (one of each minimum) have to be within two kilometers of this area, and in a radius of ten kilometers of areas of income equal or greater than $50,000, for the determination of the location of the Vertical farm.

- The author has considered the income factor as major driver to justify that all the product will be sold, given the assumption that the high socioeconomic status , which is the one that can also afford to buy organic food, cares about diet and organic food, and are the ones who will buy it.
- The author also assumed that the brownfield is not contaminated, so there will not be additional costs of decontamination. Under the European definition it can be considered brownfield even when not contaminated.
- The carbon footprint is assumed to be a result of only electric demand from the supplemental lighting.
- It is assumed values for lettuce in general, without specifying a variety.
- It is assumed that the 10th floor of this vertical farm has a carbon footprint of zero, because it would work with sunlight and no with supplemental lighting.
- Assuming that the lettuce is evapotranspiring all the time, and the same amount.

1.7 Limitations

The limitations of this thesis are the following:

- This thesis does not aim to make future projections and trends in the evolution of technology.
- The development of the thesis has been done without the use of prototypes or experiments with plant growth because of time constraints.

- The cost of energy and water are not constant either in time or geographic location, which means that depending of the crop it will require different amounts of water, as well as the location where the vertical farm is going to be built, if that hypothetical area depends on coal, gas or renewable energies it will affect the cost of energy and also the carbon footprint. So even that this study pretended to be an example that could serve anywhere, it is obvious that depending of the geographical location will affect those parameters.
- There is no data available or existing for ArcGIS in order to classify the areas by cost of land or property.
- The results given for lettuce are not applicable to other crops.

1.8 Delimitations

The delimitations considered by the author for the development of this thesis are the following:

- This research did not focus in the robotization of the food production process.
- The author did not intend to design a new model of vertical farm.
- The research conducted by the author did not analyze all the social implications derived from building a vertical farm.
- The author did not intend to study the feasibility of vertical farming as a method to recover brownfields.
- The author did not study all the crops. This thesis is focused just in leafy greens, specifically lettuce.

- The author did not include in the study the costs of packaging, ventilation or installation of other devices such as dehumidifiers.
- The author did not put special emphasis in the distribution chain because it is assumed zero losses in distribution and delivery of the product.
- The author has not analyzed the amount of sunlight and shade positions made by the buildings of the cities in order to find a location suitable for the vertical farm. Some of the criticism to vertical farm located in cities is that the producers will not be able to use natural light or to install solar panels in order to produce electricity because of the shading of the other buildings.
- The research conducted by the author did not analyze in depth how indoor grown lettuce with artificial light affects its nutritional value.
- The relative demand of labor and costs of building construction and land purchasing are out of the scope of this thesis, although the author is going to quickly estimate the land efficiency of the vertical farm production.
- The research of nutrient requirement is out of the scope of this thesis.
- The comparison between VF and conventional farm is out of the scope.
- The estimation of carbon footprint is based only in the relative demand of electricity from the artificial lighting.
- It has been used an average number for the different varieties of lettuce, and this can cause alterations in the real data if calculated for a specific variety.
- One of the assumptions is also a delimitation. Considering that the carbon footprint of the 10th floor is zero because does not use supplemental lighting

is not real. But the author is not taking in consideration the embodied carbon of the materials, nutrients, or others materials.

1.9 Summary

The researcher has introduced his proposal, defining the scope and significance, as well as defining the most important concepts of the study, its assumptions, limitations and delimitations. In the next chapter the author investigates the literature relevant to this study.

CHAPTER 2. LITERATURE REVIEW

In this chapter the author has developed a deeper search of the existing literature in the different fields related with vertical farming. The motivation to research vertical farming is because it's an innovative technology that is complex since the project would involve demographics, water, energy efficiency, cost analysis, transportation, informatics, for sustainable food production. The diversity of the areas of knowledge linked with the vertical farming concept is a challenge for modern day society as food is becoming more difficult to grow as the population of the world increases.

2.1 Methodology of the Review

The databases that the author has used are Google Scholar, Science Direct, Springer Link, Purdue libraries, UPC library and DIT libraries.

- Content Analysis: The author has analyzed reliable sources of data from different research institutions, universities, and commercially viable facilities, in the form of scientific articles, journals, conference proceedings, emails and face-to-face meetings.

- Interview: The author has arranged meetings with experts in the field (most of them are professors in different areas of Purdue University and Cornell University), and sent emails, phone calls and personal communication, in order to collect more data for the analysis research in the following stages of the thesis.
- Surveying: Blog (Weblog) and video blog post, online lecture notes and presentation Slides, scientific journals, conference proceedings, technical reports, books and magazines.
- Analysis: The author has analyzed the data provided by the cited studies in the references of the present thesis in order to identify the different types of artificial lighting that exist, analyze them and to be able to choose the most suitable option for indoor lettuce production. The author also analyzed the cost of energy under the kind of light chosen. This thesis also focuses in the amount of water consumed by the hypothetical vertical farm. The author followed the same logic that with lighting, which is first, identify the hydroponics systems available and feasible for indoor lettuce production at commercial level, and analyze how much water will be consumed. The parameters of energy and water will be defined in relation with the amount of lettuce produced for the location "X".

  For determining the location "X" of the Vertical Farm used in this thesis the author has used ArcGIS software. The author has created informatics models under parameters specified by the author himself under the supervision of experts in GIS, in order to locate the most suitable location that follows all the requisites. Surveying has helped the author obtain information about studies that are currently being done in the same field as this thesis. It also has shown different technical solutions that are linked with vertical farming around the world through a variety of different experts in their respective fields. The idea of the vertical farming has brought all of these experts together.

Gotham greens (2008), is a company located in Brooklyn, New York that produces locally grown leafy greens. The company uses what they call rooftop farms to produce fresh vegetables that will be served in the local restaurants and establishments. This is under the commercial and business point of view.

The objectives for the companies like *Gotham greens* are to grow the highest quality plants in a commercially viable size, using the known and successful technologies.

The process of building a vertical farm has proved to be complex, which is shown in figure 2.1., where it can be read the factors involved in the crop selection when growing in a controlled environment or vertical farm. It is just not a greenhouse design and the growing system layout. It is necessary to study the market and the consumer's needs, which is out of the scope of the present study. Both the selection of crop and the site selection are crucial for success. The location is very important in order to know if there are any legal barriers, which is not considered in the present study, for its construction or the permitting regulation.

The climate control associated with energy costs of the vertical farm or greenhouse includes: lighting, heating, ventilation, cold storage, irrigation and pumping in order to keep stable conditions to produce year round.

The water is another key factor to know if make a vertical farm is really affordable. The movement of water is a challenge, as well as the load and height restrictions in the structure of the building.

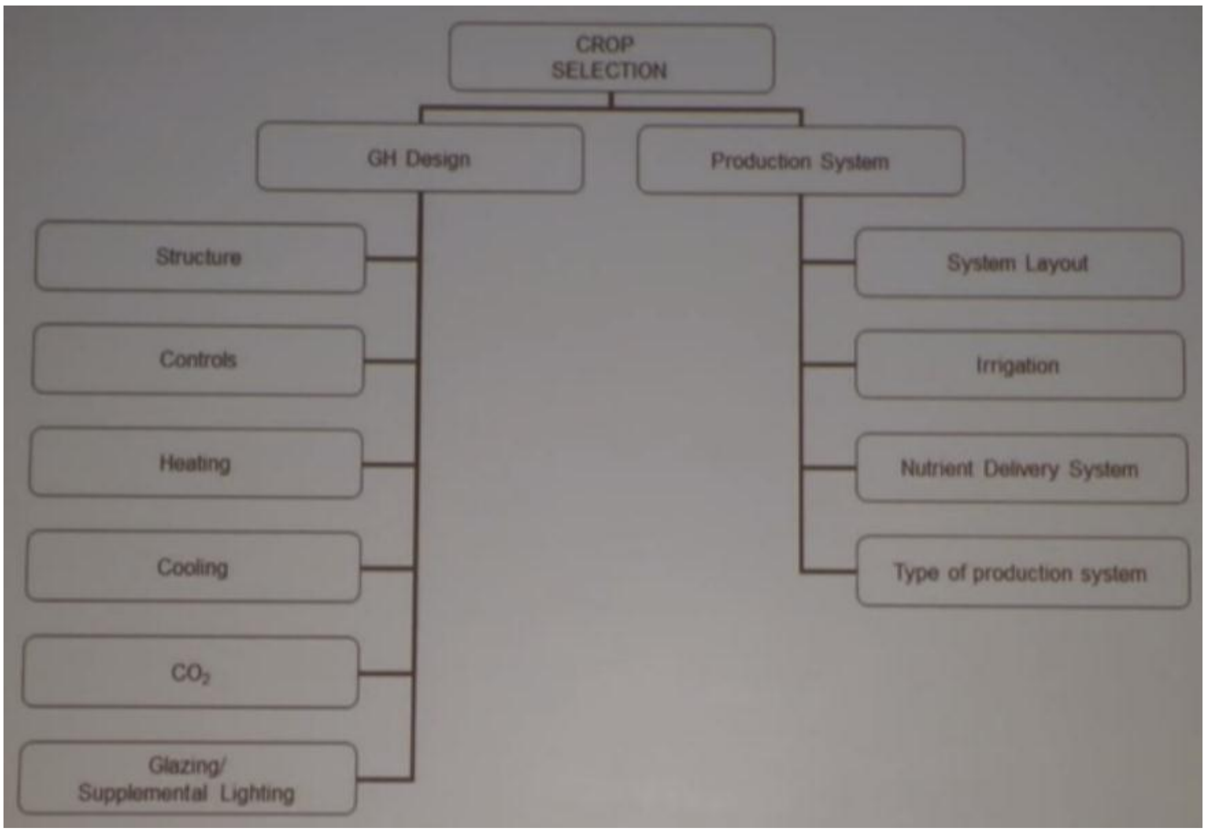

Figure 2.1 Factors to consider when building a VF
(Nelkin, J. 2012)

The author has been in contact with *Sweet Water Foundation*, a non-profit organization in Chicago, which have provided by email of useful information for the development of this thesis.

2.2 A Change in the Diet of Rising Economies

As the middle class of China and India gains more wealth, which is what everybody wants, they demand more meat in their diet. The global meat production is expected to multiply by two by the year 2050. What aspects of food consumption will we need to change in order to meet the challenges of food production? Pachauri, Nobel Prize winner and Director of the Energy and Resources Institute, (BBC, 2009) has the opinion that the solution is as simple as eating less meat (less animal protein). As incomes increase, so the consumption of meat goes up substantially. Cattle are fed with large quantities of food (grain). If less meat was consumed then production that produces animal protein perhaps could be used to feed humans directly. Some of the examples are: 23 kg grain to produce 1kg/lamb, 15 kg grain to produce 1kg/beef, 6 kg grain to produce 1kg/pork, or 2.5 kg grain to produce 1kg/chicken. (BBC, 2009).

Livestock farming uses one third of the free land, includes the land dedicated to growing crops for animal feed, 10% of the annual water consumption and represents 20% of the greenhouses emissions, mainly cows.

In America the last six to eight months of a cow's life are spent on feed lots, which means that people can find 10,000 to 100,000 animals fed intensively (growth hormones and antibiotics) and they essentially double their weight.

The American system focuses on profit and the amount of kilogram of beef that one can get per dollar invested. One must see the animal as part of the ecosystem. Eating grass instead of grain will cause the price of meat to increase and there will be less production, so the population will have to eat other sources to obtain proteins, and there will be a need then to produce more vegetables. (BBC, 2009).

The supermarkets in Europe have to change their policies. Supermarkets reject products that are either scratched, beaten, a different color and/or are a little dirty, hiding behind the European regulations, telling people that they give the consumer what the consumer wants, and that by doing so, they reduce waste.

In one of the reports of Oxfam International (*Band Aids and Beyond: Tackling disasters in Ethiopia 25 years after the famine*, 2009) was said that aid given in food relief could be part of the problem. Some food distribution is helpful, but often, when a large amount of wheat or maize is shipped from America, what happens with a lot of that food; the aid to the poor country of destination receives the food too late, just in time when their own farmers are harvesting. So the food arrives, crop prices drop, and the local farmers take a loss in their market. Aid can actually be a deterrent to recovery if it is done in the wrong way. Giving people food is not always the right response.

Oxfam suggests that the best support is to give money. Money is preferred because it provides choices and dignity and also stimulates locally produced products.

Rich countries with no land, for example Qatar that has money from oil, want land for its own food, and this is an issue. So countries like Qatar with no land trade with Africa for land because hunger pushes them to do so. However, this means that thousands of locals from Africa or the country that sells their land will be displaced and locals may go hungry because their lifestyle has been taken away from them for government use and international trade. Land ownership is an issue that can cause violence and troubles.

In the 2008, all the world saw in the Middle East and northern African countries the rising of common people against their governments (mostly dictatorships) because of the increase of the price of food. This increase was affected by several factors and one of them was the enthusiasm of producing crops for biofuels, instead of growing food crops. Only in the U.S. one-quarter of the maize is used to produce biofuel.

The EU also has policies that say that the percentage on the car fuels of biofuels has to be up to 6% by 2020. The biofuel for the rich, however, cannot come at the expense of the poor.

2.3 Innovative Strategies

After the presentation of the current situation, the author has focused on explaining the different strategies that are emerging in different parts of the world with the aim of correcting and, as far as possible, eliminating the problem.

As mentioned in the introduction, estimations of population show that human beings will reach nine billion people by 2050 (Despommier, 2010, p.37). Maybe as many people who are able to should start growing food in their backyards as done in the past and strive to be as self-sufficient as possible. When the price of the food rises, individuals will then have sustainability and food security if they are producing their own goods.

How are governments going to provide food security in the decades ahead? People can grow more food, but the doors of trade cannot be closed. Human beings are in a world where most of them assume there are all kind of products all year round, and this is not sustainable. People should encourage our local farmers to produce either more food or the population to consume less.

People must start introducing technological solutions to food sources and production that are being investigated around the world and this thesis will explore some of them in detail.

Is there a green revolution bound to happen in the XXI century?

A strategy used in the USA for more than 20 years has been using genetically modified organisms (GMO) and products with apparently no negative effects while increasing the yield and reducing the use of pesticides. But the real situation differs a bit from the ideal situation. Every year farmers have to use higher amounts of herbicides because of the grasses that grow around the GMO crops. The GMOs have the ability to displace horizontally genes, i.e. between species. This movement of genes can produce hybridization of the other plants and they generate more resistance. The final beneficiaries of this situation are the companies that produce the herbicides and/or pesticides and the seeds of the GMOs. In the Documentary *Vanishing of the bees* (2009) and also according to Bruges (2007), it is explained the effect of horizontal genetic cross and its negative effects on bees when bees are in contact with GM plants. The final beneficiary of this situation is the company that produces the herbicides and/or pesticides and GMOS seeds.

As Albert Einstein said, “If bees disappeared from the earth, man would have only four years of life left. No more bees, no more pollination, no more plants, no more animals, no more man.”

Some scientists believe that GMOs would spread uncontrollably, and once in the market, GMOs could contaminate non GMO crops, so that all would become GMOs. This can provoke a loss of biodiversity, which is a real concern in Mexico and its thousands of varieties of corn. There are so many unknowns when talking of

GMOs, one being that the scientists do not know what the dangers might be or implications of contamination by GMOs. The integrity, for example, of the maize would be compromised with the insertion of different types of genes, and people do not know how it would affect the environment with the different complex interactions of other organisms. The consequences of GMOs are unpredictable; it could be the origin of mutations that are not possible to anticipate, and this raises concerns among the population and much of the scientific community.

Some say that people could use more wisely the resources that people have now and reduce the amount of waste. One third of the food that is produced for consumption is wasted; this means 420 pounds per household per year. There is an example of adapting new technologies in order to provide electric energy in Bedfordshire in the United Kingdom (UK). The neighbors of this town of the UK separate the organic wastes that are taken weekly to an anaerobic digester. There they are liquefied with a process of fermentation and pasteurization, which produces excess energy that goes back to the national grid and, most importantly, the organic matter after the process ends up as fertilizer for the farm.

This example could turn 30,000 tons of food wastes per year into enough useful material to provide electricity to 1,700 households and replace 300 tons of fertilizers, which is about 1,750 acres worth of fertilizer that would be normally applied to the fields (BBC, 2009).

In the U.S., Dickson Despommier, the professor of Public Health at Columbia University, devised the concept of the 'vertical farm'. To paraphrase his words the idea is quite simple, instead of having flat greenhouses, why do we not stick them one on top of each other. In this project the author uses the concept vertical farm, but not in the same exclusive terms that Despommier, in the present study 'vertical farm' will be equivalent to controlled environment greenhouse or plant factory.

2.4 Previous Studies in Vertical Agriculture

In this section of the review the author describes the research of what has been done in the matter of vertical farming, the results of previous key studies, and questions that have not been answered yet.

The challenges in vertical farming that the author identified through the process of surveying the literature were:

- Who wants to build a vertical farm, and why?
- What specific problems does vertical farming address or solve?
- How should be the operating model? Private, public, research-based, non-profit or for profit?
- Cost-benefit analysis. How is the ratio investment/return of capital? It has to be considered also that the building of the vertical farm can be of property or rental. The costs of these will be different depending of the city. The cost for energy if using 100% artificial lighting?

- How much water is used? What systems are involved in the control of the environment? What are their costs in terms of energy and money?
- What kind of crop?

There are multiple factors involved in the functioning of the vertical farm. The author created a conceptual map as method of review of the complexity and multiple factors that are interconnected and parameters involved in the vertical farm; which is shown in figure 2.2. This thesis but is not going to be as broad as the whole system and is going to focus in depth in the energy and water consumption.

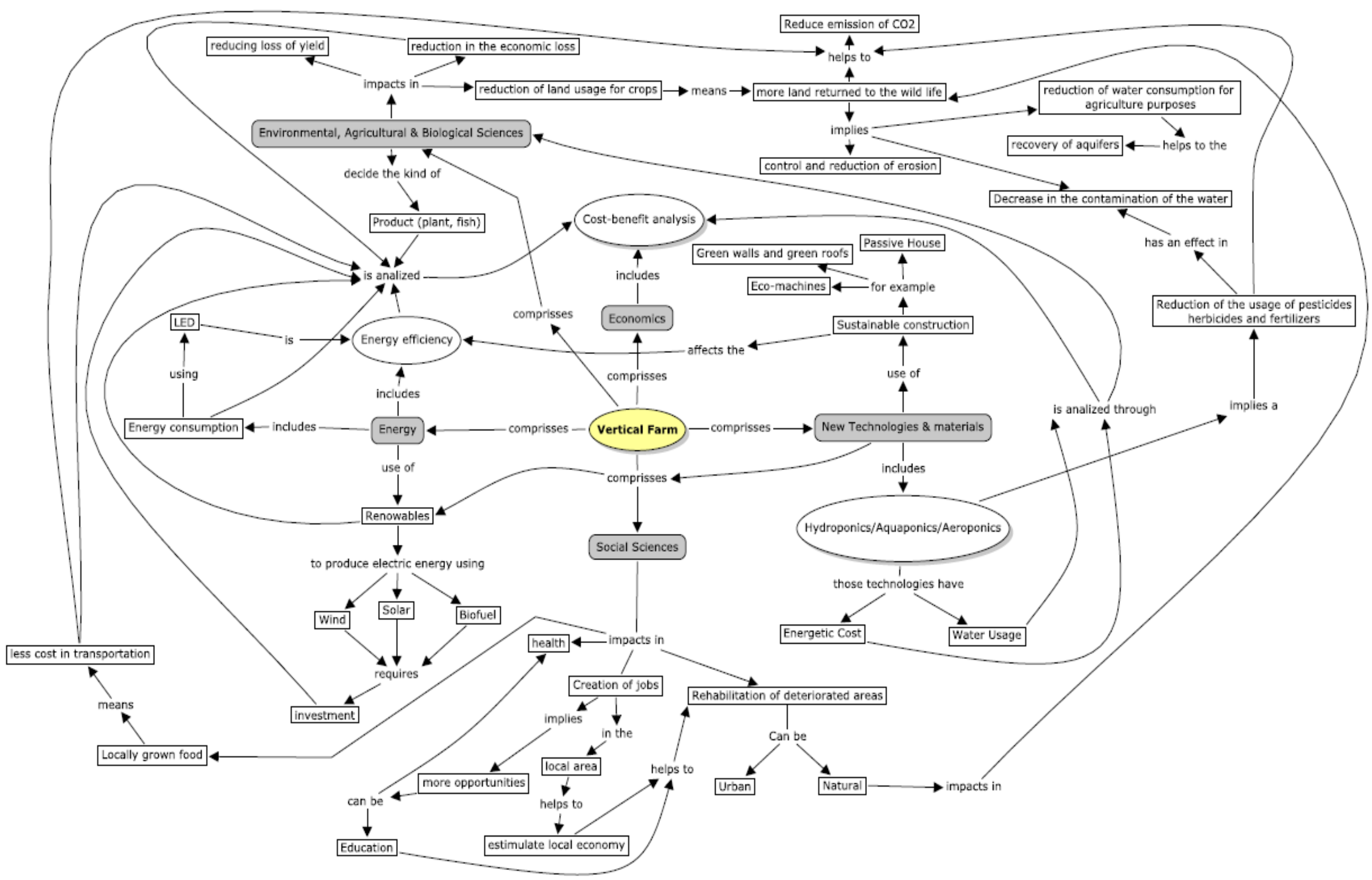

Figure 2.2 Basic relationships in Vertical Farming.

The University of Arizona in its workshop of 2012 "Technological Opportunities in Indoor Food Growing Systems: Working examples of South Pole and Moon Applications" showed the systems for their Hydroponics and Controlled Environments with the objectives of growing a food product, or create a better quality of life, or establish an outreach/educational opportunity. The results of the study of the University of Arizona in Tucson, showed 10 – 13 g per kWh grams of fresh, wet-weight, edible biomass produced per electrical power required

Where energy included:

1. for lighting;
2. for environmental control;
3. for monitoring & services

The research that University of Arizona did is not optimized for any crop (Not maximizing crop productivity) having one environment and crop culture for all. The analysis of the present thesis will be focused just in one crop, lettuce. As a result of the scope of the thesis the author has considered relevant the findings of the researchers from the University of Arizona related to lettuce, herbs, and greens, which are 10 kilograms per week or 22 lb/week harvest. (University of Arizona in its workshop of 2012 "Technological Opportunities in Indoor Food Growing Systems: Working examples of South Pole and Moon Applications.

2.4.1 Analysis of Closed Systems

Organizations like NASA, in its Controlled environment agricultural (CEA) for space has studies (Controlled environment agricultural (CEA) for space: some observations from NASA, 2012) that says LED luminaries are the most efficient lamp options and are needed in red and blue to make the plant environment optimal. The red light is for the photosynthesis and the blue light is for the photomorphogenesis of the plants. Their idea is to make possible the production of food in a closed environment.

Their findings are that to increase the harvest index it is necessary to increase the ratio edible/total biomass of the plant. If we can increase this proportion we will be having more productivity per unit of area and reducing the waste (which is an issue).

It is necessary to understand the relationship and factors that are implicated in each process to be able to succeed in the creation of a close environment optimal to grow crops, as is the case of this thesis. The figure 2.3 helps to understand better how our life cycle connects with the life cycle of the plants, and how together become the one input of the other and retro feed each other. The figure below represents the conceptual base of what is happening inside of a vertical farm.

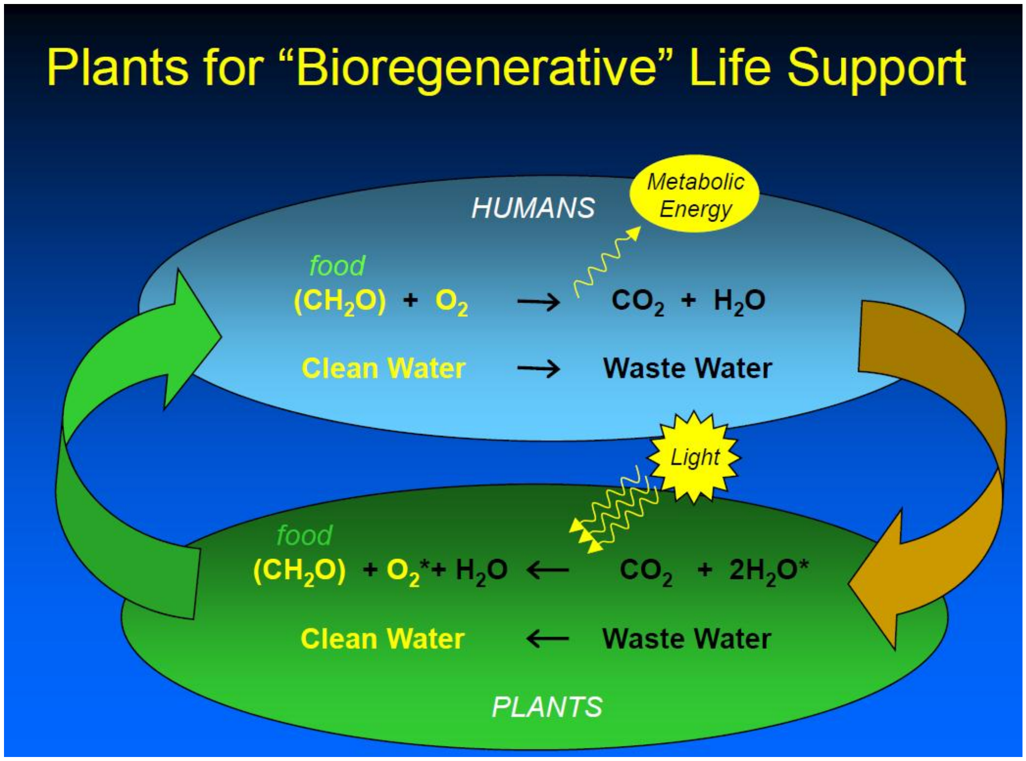

Figure 2.3 Relation humans-plants (Wheeler, 2012, p.2).

NASA has decided that the most optimal technique to manage the water is using recirculating hydroponics. See some examples and the advantages of this system in the figure 2.4, such as conserve water and nutrients; eliminate water stress, to optimize mineral nutrition, and to facilitate harvesting.

Figure 2.4 Examples of crops with 'Recirculating hydroponics' and its advantages (Wheeler, 2012, p.5)

The understanding of the environment and the horticultural considerations, gave them very positive results in increase of yield in crops such as wheat, soybean, potato, lettuce and tomato. The relation of the photosynthetically active radiation (PAR) to conversion to biomass is key to understand how much energy is needed to produce how much of food.

"Assuming a maximum 12% conversion efficiency from PAR to biomass the investigator of the NASA estimated that 1.6 g dry mass / mol PAR" (NASA, 2012, p.12). These are the results of controlling the light and CO_2 enrichment to the most optimal level for each crop and the figure 2.5:

- Wheat: 3-4x World record.
- Potato: 2x World record.
- Lettuce: Exceeded commercial yield models.

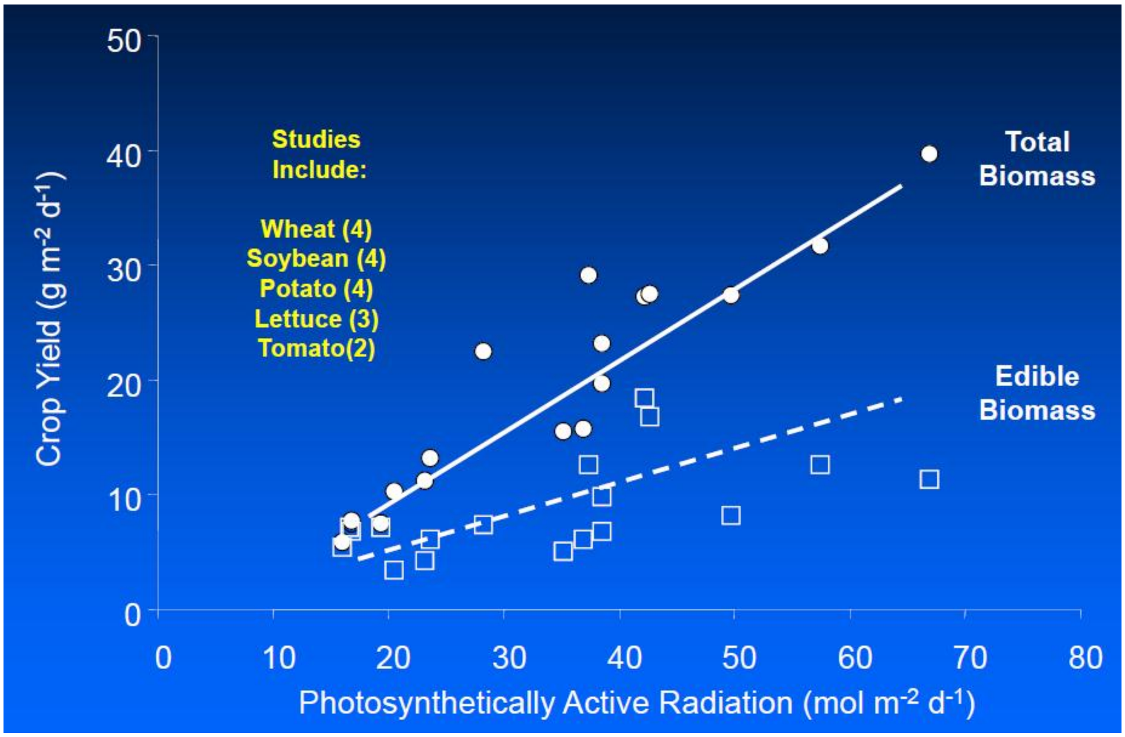

Figure 2.5 Effect of light on crop yield (dry mass)
(Wheeler, 2012, p.24)

The figure above shows in the y/axis is the Photosynthetically active radiation, often-abbreviated PAR, which designates the spectral range (wave band) of solar radiation from 400 to 700 nanometers that photosynthetic organisms are able to use in the process of photosynthesis.

The figure 2.5 though in where it can be seen lettuce versus tomato, for example, is not a fair comparison because one eats all the lettuce plant, except for the roots, but not the vines and leaves or roots from tomato.

The use of robots for the work in the harvesting of the crops is still in developing phase. Under the point of view of Naoshi Kondo, professor in the Graduate School of Agriculture, Kyoto University, Japan, the commercializing robots and robotization of the food production is still cannot compete because of: Slow operation speed (1/3 or less than a person), expensive cost (x3 times more than a person) and the necessity of changing plant training system and cultivation method (Kondo, 2012, p.9).

2.4.2 Land Use

In his thesis, Graff (2011, p. 69) said the use of land by conventional agriculture is equally inefficient. Vertical farming addresses the land requirements of agriculture in three key ways. The first and most visually apparent is the farm's use of vertically stacked floors, each of which increases the area for crop production without increasing the farm's consumption of land. The author of the present thesis however, considers, based on the comments of professor Albright via email, that this statement is misleading. "To go from field production to a greenhouse is already perhaps a 20x decrease of land area used. A 1:20 improvement of land use, or 95% savings. He doubts we are so short of land that we need to go further. The advantages of multiple floors shrink, whereas the problems of construction, work

flow, etc., grow rapidly. For example, to add a second floor is a 1:40 benefit, or a 97.5% savings – compared to 95% savings with just a greenhouse, and so on.
Note – the 20:1 ratio is for lettuce only and much of the benefit comes from spacing and re-spacing of the plants, which cannot be done in the field. Tomato or other crops would be a very different story."

Next, a vertical farm's aforementioned ability to perpetually generate the ideal growing conditions for each plant while protecting crops from harmful pests and weather-related disturbances ensures more harvests and less plant loss per acre than conventional farming. The effect of a contained environment is more difficult to quantify in terms of space efficiency, owing to the fact that some plant varieties offer more opportunity to improve their harvest efficiency than others.

It was discovered for lettuce, the yield equivalent of Cornell's S/CEA facility is 470 tons per acre per year - over twenty three times more productive than the typical California lettuce farm's yield for the same land area (Graff, 2011, p.69).

2.4.3 Types of supplemental lighting

There are several kinds of lighting, but in this section of the thesis the author is about to explore the right ones for controlled environment, greenhouse and vertical farm uses.

According to the article *Managing Photoperiod in the Greenhouse* of Christopher J. Currey and Roberto G. Lopez of 2013, managing the photoperiod is an important aspect of greenhouse environmental management. By understanding the natural photoperiod and the techniques used to manipulate photoperiod, you can achieve desired plant responses, such as accelerated flowering to reach target market dates more reliably. To create (night interruption) NI or day-extension (DE) conditions in a greenhouse or controlled environment, a grower has several choices. Some of these choices, plus their advantages and limitations, are:

- **Incandescent (INC) bulbs**. These are commonly used in greenhouses to provide DE and/or NI lighting. INC lights may be used for cyclic lighting, because the frequent on-and off will not affect bulb life or fixture longevity. INC bulbs are inexpensive and emit an effective spectrum, but they are very energy inefficient and require high power availability. Screw-in compact fluorescent bulbs (CFLs) pose an attractive alternative to traditional INC lamps for DE and NI lighting. While CFLs are more energy efficient and are effective for use on many crops, their spectrum is not as effective at controlling flowering of some long-day (LD) plants. CFLs are low in far-red (FR) light, which is required for rapid flowering of some LD crops like pansy and petunia. It is possible to alternate CFL with INC bulbs to provide the required light quality for effective photoperiodic lighting and still achieve some energy savings. (Currey, J. C., Lopez, R.G. and Runkle, S. E., 2013, p.4)

- **High-intensity discharge (HID) lamps**. HID lamps, such as metal halide and HPS lamps, may also be used effectively. There are several ways to use these lamps to provide DE and NI lighting. Most commonly, HPS lamps are suspended above the canopy. Another method is to mount HPS lamps on booms that move over the canopy. The newest development in HPS lamps is to use an oscillating reflector. (Currey, J. C., Lopez, R.G. and Runkle, S. E., 2013, p.5)

- **Light-emitting Diodes (LEDs)**. This technology is an emerging light source with promising plant applications, including the regulation of flowering. Their long lifespan, energy efficiency, and ability to target specific wavelengths of light make them a viable option for managing photoperiod. LEDs also provide the opportunity to adjust the ratio of red (R) and far-red (FR) light for desired plant responses. A low R/FR ratio promotes stem elongation in many plant species, which is a shade avoidance strategy plants developed from being shaded by neighboring plants. The best combination of R/FR and red/ blue is still being studied, but we do know that FR light is important in promoting flowering in LD plants. Early studies show that LEDs that emit both R and FR light are similarly effective as INC lamps. However, more research is needed on a wide variety of ornamental plants (Currey, J. C., Lopez, R.G. and Runkle, S. E., 2013, p.5)

According to research of Torsten Wik in Chalmers University of Technology, in 2013 in Sweden, retrieved from http://www.chalmers.se/en/news/Pages/Plants-communicate-what-type-of-light-they-want.aspx ,

> ”The light spectrum provided by high pressure sodium lamps corresponds very poorly to the spectrum plants use during photosynthesis (see figure 2.6). Plants do not receive very much of the blue and red light that they need the most. They do, however, receive a great deal of infrared light, which is harmful to some crops, and yellow light, which the plants cannot utilize to any great extent.”

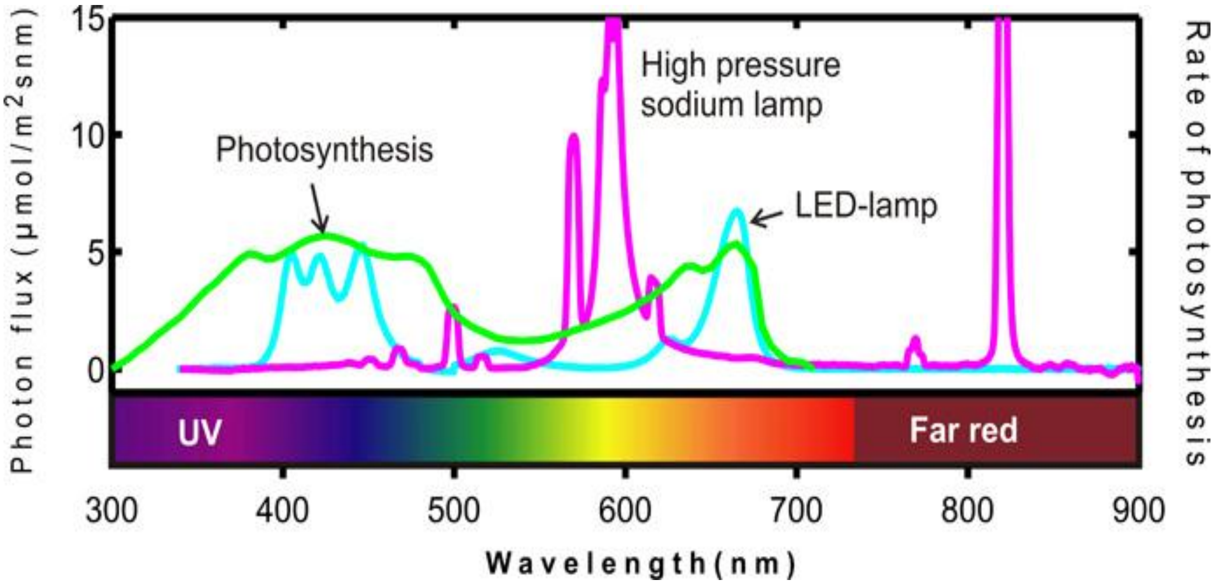

Figure 2.6 The diagram shows: 1. How the efficiency of photosynthesis depends on wavelength (green). 2. Wavelength content for regular sodium lamps (pink). 3. Wavelength content for an advanced LED lamp (turquoise). (Wik, 2013).

> The Swedish research wanted to "produce a system that employs the plants' response to automatically regulate the lights in the greenhouse. Natural sunlight can then be supplemented with light from lamps to ensure the total lighting is that required by the plants, both in terms of brightness and light spectrum." (Wik, 2013)
>
> In their words "This can be achieved using advanced LED lamps, which consist of several groups of dimmable light emitting diodes with different color spectra. This kind of lamp can also be programmed to provide lighting that is adjusted to the needs of the plants." (Wik, 2013)

That coincides with the other literature in selecting LED as the source of supplemental light. LED is designated as the technology with higher potential for energy saving, by regulating the lights intensity and spectrum using the method developed in Chalmers University.

2.4.4 Limitations of Growing Plants in a Closed Environment

The limitations of having plants growing in a complete closed environment are that the plants keep the concentration level of CO_2 optimal but the concentration of O_2 in the air increases, which is toxic for humans when reaches certain limit. The concentration of gases, such as CO2 is one of the limitations of an entirely enclosed facility should solve, as well as the humidity, which will be analyzed in the chapter five of the present study. The emission of ethylene into the air it is also a problem that can affect negatively the development of the crops. In the following graphic it is shown the evolution of ethylene in ppb through the growing process of the crops.

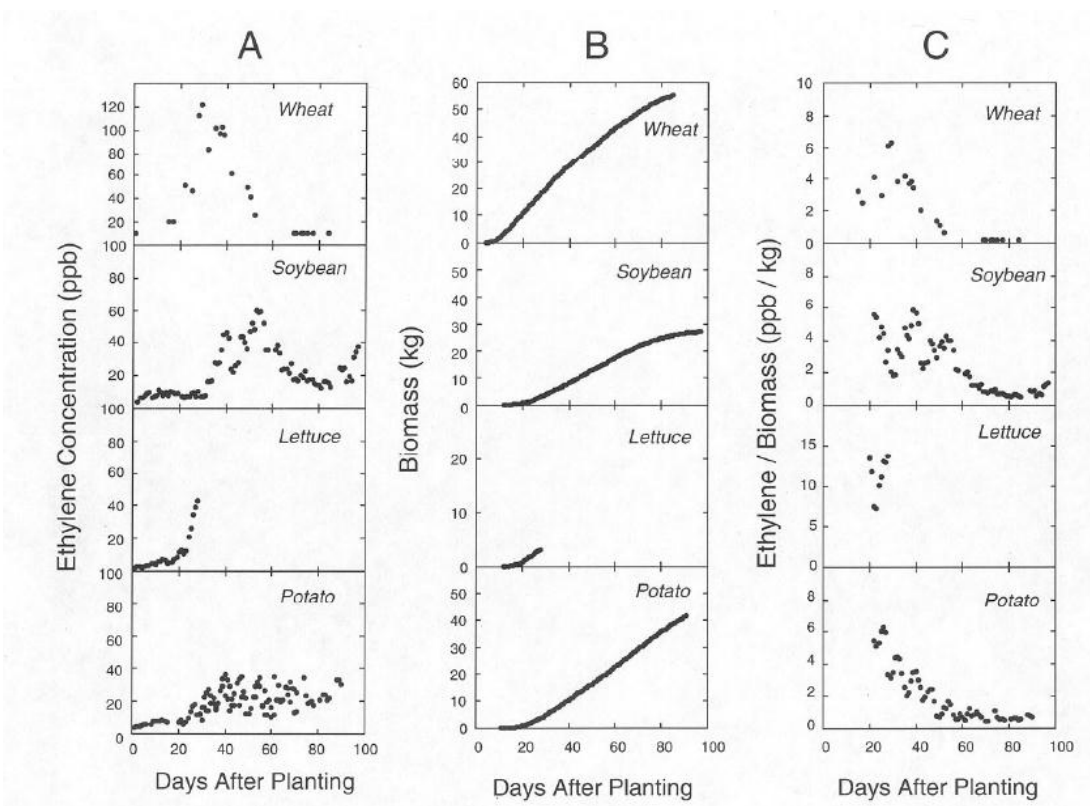

Figure 2.7 Canopy/Stand ethylene production
(Wheeler, 2012, p.15)

Similarly the German Aerospace Center has a study called CLOSED-loop life support systems that says that plants can close the three loops:

- Regenerate the air (as seen in the figure 2.7 the crops listed generate dangerous levels of ethylene in the air)
- Regenerate the water
- Produce food

All of them in one, these applications on earth fit with the idea of vertical farm. The German Aerospace Center did a cost analysis and studied the profitability of the project, comparing the results of the vertical farming with the conventional farming. The study concluded with five main points or questions.

- They had to see and investigate the optimal design of the building
- They needed to contemplate the several production processes and decontamination processes.
- Light and nutrients for the best optimum grow of the biomass (for each crop will be different).
- Energy saving techniques, for example LED, to put them in a frequency so they LED can go on and off in a specific frequency. The plants usually do not recognize that but much better shutter cycle, and some energy can be saved.

- Efficiency, how much energy do we need to put in? How much resources do we have to put in? And what do we get out? What is the kilogram price? How much energy it would take outdoors to grow the same amount of food that you produce in the vertical farm?

2.4.5 Cost of Designing Vertical Farm – the facility

The Vertical Farming movement has taken strength in the Chicago area. One of the key factors that Martin Felsen defends in his presentation in September 2012 *Civic Interest in Designing Vertical Farm*, is the need to engage the corporate leaders to this idea.

In his presentation he pointed that his group of study, from *UrbanLab*, is considering the Stockyards Industrial Park of Chicago (a place that now is full of empty factories and abandoned infrastructure) as location to develop his Vertical Farming design. The number one opportunity of working with public officials is that, as long as his group of research develops this idea, the land on the Stockyards Industrial Park will be free. One can estimate (Felsen, 2012, p.1-9) to build a Vertical Farm by using the Life-Cycle Cost Calculation (LCC). After identifying all costs by year and amount and discounting them to present value, they are added to arrive to the total life-cycle costs for each alternative:

LCC= I + Repl - Res + E + W + OM&R + O

LCC=Total LCC in present-vale (PV) dollars of a given alternative.

I = PV investment costs (if incurred at base date, they need not to be discounted).

Repl= PV capital replacement costs.

Res= PV residual value (resale value, salvage value) less disposal costs.

E= PV of energy costs.

W= PV of water costs.

OM&R = PV of non-fuel operating, maintenance and repair costs.

O= PV of other costs (e.g., contract costs for ESPCs or UESCs).

Costs to build Vertical Farm:

- 10 story, one acre vertical farm = $41,577,500
- New bio solids energy plant = $8,065,600
- New accessory building - offices, labs, etc.= $16,049,700
- Site and infrastructure improvements = $12,472,000

Total= $78,164,800, under the estimations of Felsen and his group.

In this thesis, the author has used the formula used by *Urbanlab* and some of the values shown as reference of his estimations of cost for a Vertical Farm in the location “X”, which will be located in the chapter 4 of the analysis and the appendices.

The key findings of the research of Felsen that have been useful for the development of this thesis are:

- When working with public sectors is important the engagement of these.
- It is also important to build a prototype when presenting a project of this scale. In this thesis the author does not have a main objective to design a new

model of a Vertical Farm, but show how to apply it to satisfy the food needs of a population “X”.

- Expand the working group. The author of the present study has met with several experts in different areas related with Vertical Farming, such as professor Cary A.Mitchell of Horticulture at Purdue that is an expert in controlled environments, and professor Vincent Bralts in the Agricultural and Biological department and expert in irrigation systems, also at Purdue, to talk about irrigation and water issues involved in the Vertical Farm system, as well as other experts in the industry via email.

According to experience and data from the Japanese corporation Mirai, there is an increasing interest in plant factories in Japan, as well as an increasing pressure to change the structure of Japanese agriculture and food production and public concerns over nutrition and food safety. This interest receives a strong support from local and federal governments and the Japanese consumers not only accept but also appreciate the high technology in agriculture. On the other hand the dependence on public subsidies can camouflage the real economic feasibility of the plant factories project.

The author has learned from the Japanese experience that a population informed of the concerns related to food as well as members from the public sector involved are key factors for the success of this new trend/technology/project.

The Technologies (Hardware) that Mirai considers that are key for a plant factory (vertical farm or controlled environment) are:

• Production capacity (examples)

– 300 lettuce heads /day (60 m^2 or 650 ft^2 foot print)

– 10,000 lettuce heads /day (1200 m^2 or 0.3 acre)

• Hydroponic (NFT) system, the author is going to mention these systems in the next section of the literature review.

– Nutrient circulation and EC/pH control are also key technologies but are out of the scope of this research.

• Environmental control

– Thermostat-based temperature control and CO_2 control as well as all the monitoring systems are out of the scope of this research, although are mentioned.

– Fluorescent lamps and/or LEDs, the source of artificial light is one of the most important factors of the present study.

• Hygiene is another factor that is proposed as key to prevent pathogens in the facility and prevent diseases to affect the crops. Some of these technologies are; air cleaning (filtering) system, lab suit, Air shower for workers before entering, and water shower prior to access for complete removal of pathogens in large scale facilities. (Shimamura, 2012, p.5).

The tables of the figure 2.8 below shows the Mirai economic analysis of how much it would cost to build and maintain the vertical farm (plant factory) for lettuce production.

Economic analysis of indoor lettuce production

Items	Note
Building size (modular building)	1,300 m^2 (14,000 ft^2) footprint (1,100 m^2 or 12,000 ft^2 footprint for 4,536 m^2 production area)
Crop	Leafy lettuce (10,080 heads per day, 100 g per head)
Nutrient delivery and lighting systems	NFT Combination of LEDs and white fluorescent lamps
Other facilities	Office space, packing area, storage, cold storage (200 m^2)
Other equipment	Cooling/heating, seedling production systems, irrigation tanks and injection systems, climate controller etc.
Equipment/facility life	Production systems for 7 years; 15 years for other equipment; 20 years for the building

Balance estimate

Items	Income/Expense	Note
Annual gross sales	~$4.1 M (331M Yen)	~$5.68/lb (10% product loss)
Annual costs (total)	~$3.4 M (274M Yen)	~$4.70/lb
Investment return		6th year

1 lb = 0.45 kg

Capital costs: 7.4 million US dollars (590M Yen)

Items	Costs	Note
Building	180M Yen (31%)	New construction
Construction	110M Yen (19%)	Utility set up
Equipment and facilities	300M Yen (51%)	NFT systems, irrigation systems, lighting systems, others

Annual operation costs: 3.4 million US dollars (274M Yen

Items	Costs	Note
Salaries and wages	71.3M Yen (26%)	Two full time workers + hourly laborers (210 h/day, $10/h)
Materials	15.4M Yen (6%)	Packing materials, seeds, light bulbs, fertilizers, chemicals, etc.
Utilities	72.6M Yen (26%)	369MW/month power use + water use
Transportation and shipping	6.0M Yen (2%)	
Other costs	49.2 M Yen (18%)	Facility/equipment maintenance, consulting
Depreciation	59.2 M Yen (22%)	

Figure 2.8 Estimation in Yen and US dollars of a plant factory in Japan, by Mirai (Shimamura, 2012, p.21-22).

"Indoor cultivation will never be the same as 'industrial factory manufacturing' and needs a **non-linear approach** by understanding the nature of biology and agricultural business." (Shimamura, 2012, p.23).

According to Aerofarms, 2012 there are losses not only in the distribution chain that has to be under consideration but also from the seeding process. Those considerations but will be considered for further research in the chapter five in the recommendations.

2.4.6 Hydroponic Systems

The hydroponic system permits plants to grow on vertically- oriented growing structures. This allows us to make a more efficient use of the land than the use of land by conventional agriculture, increasing the area for crop production without increasing the farm's consumption of land.

Other advantages of growing plants in indoor hydroponic systems are: "The ideal growing conditions for each plant can be generated and maintained, while protecting crops from harmful pests and weather-related disturbances, which ensure more harvests and less plant loss per acre than conventional farming." (Graff, 2011, p.69).

According to the research of Gordon Graff, University of Waterloo (2011) there are four basic typologies applicable to indoor crop cultivation on a commercial scale. These consist of:

A. **FRAME TRELLIS:** The A-frame "trellis" design was the first commercially successful hydroponic system to exhibit a vertical orientation. Varieties of this design consist of pipes configured either vertically or horizontally to form a triangular extrusion of its footprint, thus increasing the available growing surface without meaningfully reducing sunlight access.

The primary advantage of the A-frame design is its simplicity, as it achieves a high degree of space efficiency while utilizing technology that has been standard in the hydroponic industry for decades. On the other hand, the primary disadvantage, according to prof. Albright, is shading/light reduction per plant. Graff (2011) p.70

Figure 2.9 An example of an A-Frame hydroponic system Ricardo's Tomatoes & Strawberries - New South Wales, Australia. (Graff, 2011, p.70).

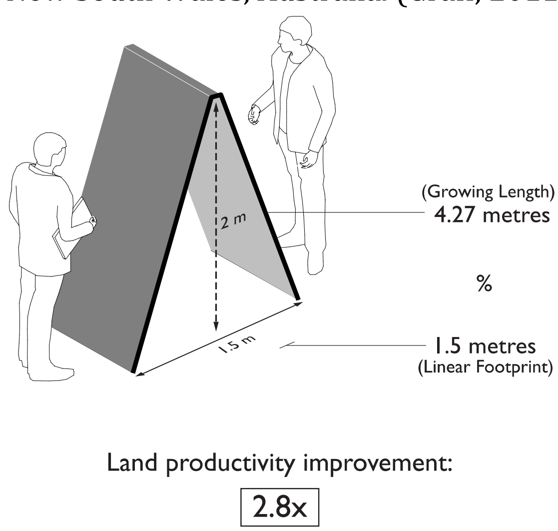

Figure 2.10 Space efficiency of the A-Frame design (Graff, 2011, p.70).

B. **STACKED BEDS:** Much like the A-frame design, the "stacked beds" configuration is extremely straightforward in concept and technology. The design is merely a stacking of the standard in-line pipe beds that continue to be the system of choice for commercial hydroponic farms. Much like the ramification of stratifying floors in a vertical farm, the design's stacked configuration doesn't allow sunlight to penetrate each layer, making artificial lighting a necessity. The best commercial example of the stacked bed approach is the design used by TerraSphere Systems, which has implemented systems with five tiers of growing surface within a three-meter floor to ceiling height. Graff (2011) p.71

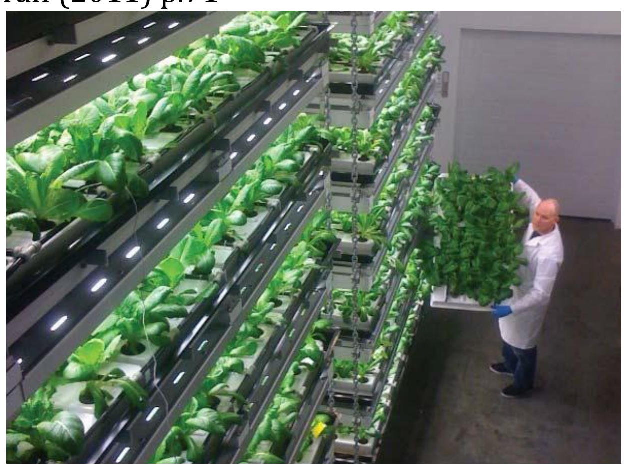

Figure 2.11 TerraSphere's indoor farm, Vancouver, British Columbia (Graff, 2011, p.71).

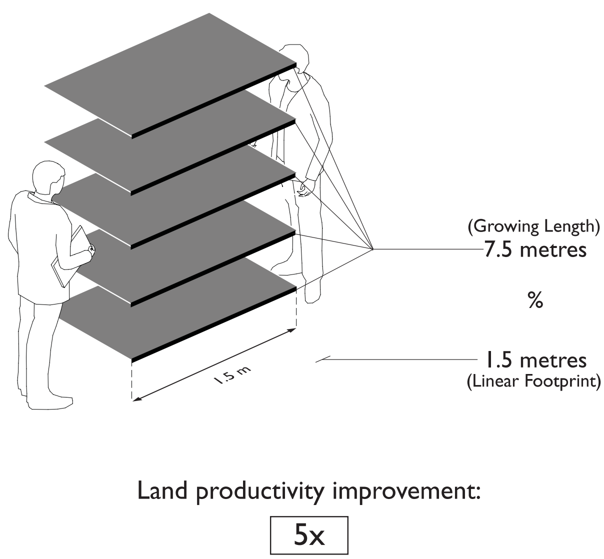

Figure 2.12 Space efficiency of the stacked bed design (Graff, 2011, p.71).

C. **STACKED DRUMS:** Though it is the least common commercial hydroponic system listed here, the drum design likely offers the most promise for the future of indoor agriculture. It consists of growing plants within the interior of a drum structure positioned around a central artificial light source, resulting in an extraordinarily low space and energy use per unit of production. The first publicized example of this design emerged in the late 1970s from the Environmental Research Laboratory at the University of Arizona. Today the most popular variant is produced by Omega GardenTM of Victoria, B.C., which features a mechanism that rotates the drum through a tray containing nutrient solution. Graff (2011) p.72

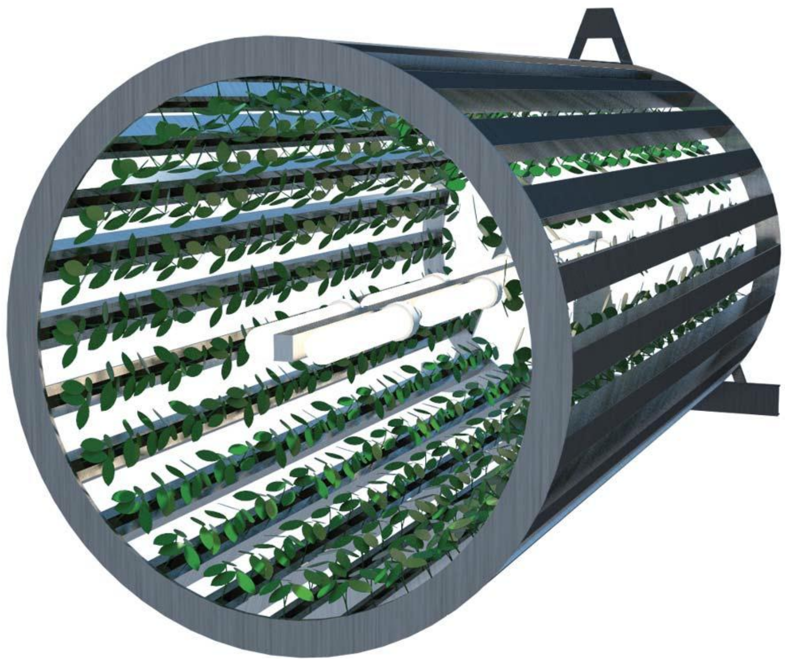

Figure 2.13 Stacked drum design (Graff, 2011, p.72).

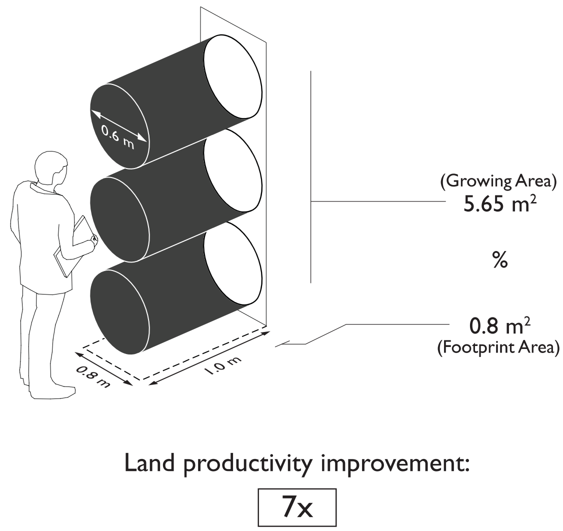

Figure 2.14 Space efficiency of the stacked drum design (Graff, 2011, p.72).

D. **COLUMNAR SYSTEMS:** The newest variant of vertical cultivation to emerge is the columnar design popularized by the English horticultural company Valcant. Their design, VertiCropTM, consists of a series of stacked trays arranged in a staggered pattern to increase light penetration. The "columns" are then cycled along a conveyor track to a central machine that delivers nutrient solution and removes the trays for harvesting. The design boasts the highest space efficiency among the sun- fed hydroponic systems available today, however, it is also the most limited in accommodating different plant varieties. Graff (2011) p.70-73.

Figure 2.15 Columnar design (Graff, 2011, p.73).

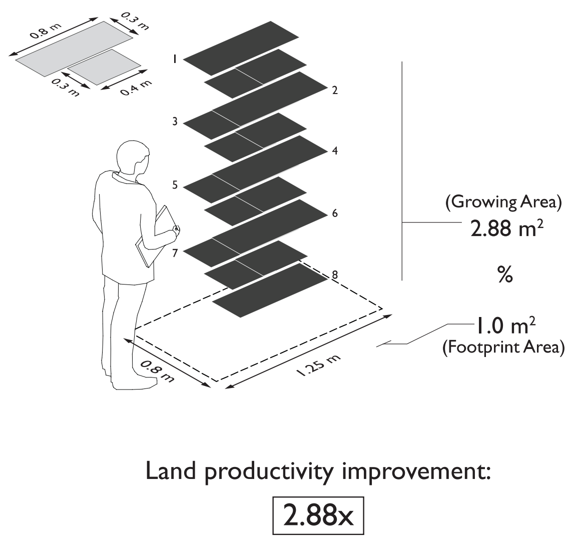

Figure 2.16 Space efficiency of the columnar design (Graff, 2011, p.73).

2.4.7 Use of water

The company *Aerofarms* uses the technology of aeroponics, which consists in spraying directly to the roots a solution of water and nutrients in a form of mist.

The technology that this company uses is an interesting example of successful Vertical Farm project around not only the United States but also internationally (Saudi Arabia and Abu Dhabi).

It is shown in the figure 2.17 below the production model used by Aerofarms:

Figure 2.17 Aerofarms stacked bed design
(Aerofarms, 2012, p.5).

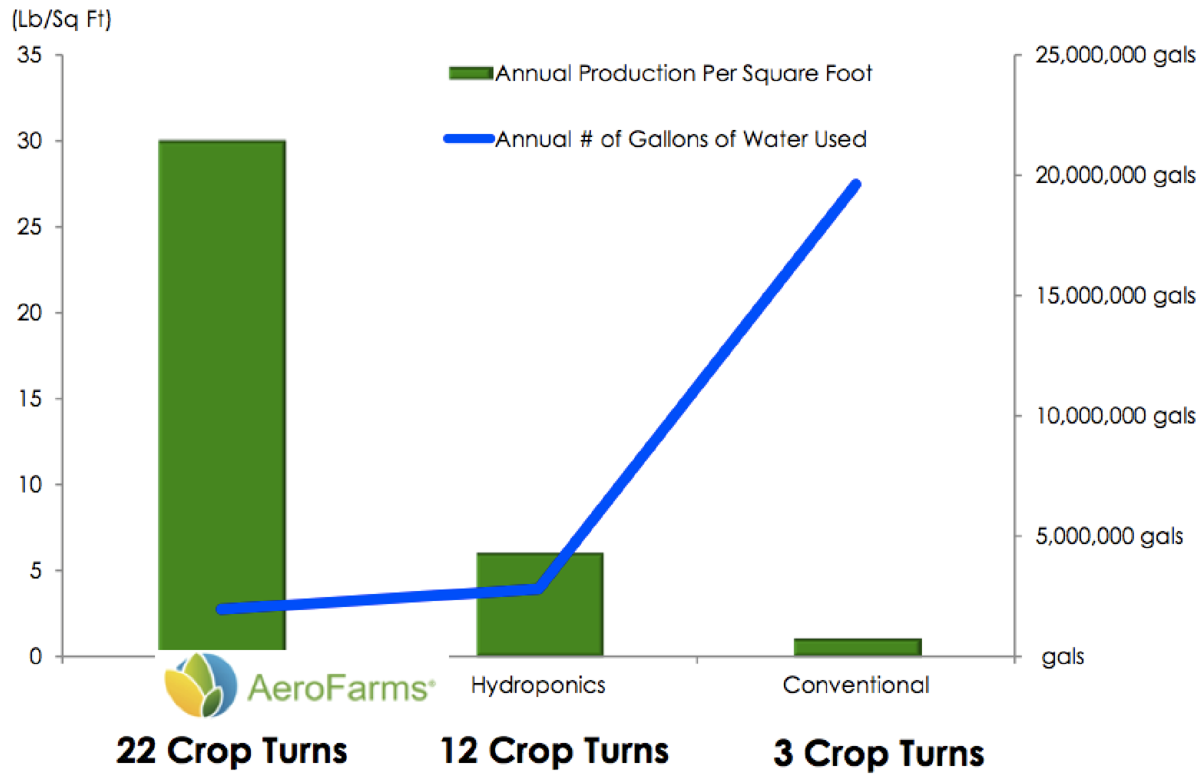

Figure 2.18 How is productivity and conservation rewarded?
(Aerofarms, 2012, p.13)

The author has considered the model of Aerofarms, and in the findings of Chapter 4 the author of the present study has presented the calculations of water usage. The author used the results of the figure 2.18 to choose aeroponics as technique to be developed versus hydroponics.

According to Future Foods Farms, from the website http://www.futurefoodsfarms.com/Future_Foods_Farms/Welcome.html, the water usage is less than one gallon of water to produce one head of lettuce in 28-30 days due to their recirculating greenhouses that support California's water conservation, (conventional (soil grown) farming can use from 10 -15 gallons of water to grow one head of lettuce taking 38-45 days versus recirculating hydroponic systems can use 4-5 gallons of water per head of lettuce.)

In parallel, in the CEA system at Cornell, they can grow one head of lettuce using just over half a gallon. The lower limit is determined by tip burn – if too little water is used, there is insufficient transpiration, insufficient calcium uptake, and tip burn appears in a few days.

2.4.8 Effects on the flavor

In a closed environment, the flavor can be affected? (commercial VF representatives say that VF food tastes better, but it is really true?):

In the article *Minimizing energy utilization for growing strawberries during long-duration space habitation* Gioia D. Massa, Judith B. Santini, and Cary A. Mitchell (2010) it is conclude that for strawberry production, it is important to note that, even in controlled environments, flavor characteristics change over time in ways not yet completely understood. They found significant variation in flavor compounds of field-grown strawberries at different harvest times, but causes such as environmental variation and fruit ripeness make it difficult to understand the impact of plant age. Controlled environment studies may allow researchers to better distinguish this factor. Interestingly, physical berry characteristics such as color and texture were independent of flavor characteristics such as sweetness, tartness, and aftertaste.

Some researches states that the fruit/crops needs changes in the environment and stress in order to increase the production of sugars, which makes the fruit sweeter, in the case of referred article, the strawberries.

Selection of day-neutral strawberry cultivars can help enable long-term, affordable production of palatable fruit in an off-Earth, plant-based life-support setting under a variety of photoperiod environments. Overall crew time and energy expenditure for strawberry production can be minimized by selecting large-fruited cultivars that perform well under short photoperiods. Staggered planting dates would buffer the time-dependent variation observed for shorter photoperiods while still allowing the reduction of energy inputs. Use of a day-neutral cultivar such as 'Seascape' that is productive under a wide range of lighting conditions will allow strawberry to be better integrated into a space plant-growth system where other demands might control environmental settings.

By making grow crops in a closed environment and controlling the temperature, light, water, humidity, and nutrient availability and delivery an optimal environment for the crops is made. Under this ideal conditions the crops grow quicker, larger, and with many more harvests per year than conventional farming.

2.5 Revisions based on validation panel feedback

- Summary of what the author of this thesis asked to the experts:

The author sent to the four members of the panel of experts different emails in order to ask for feedback, corrections, comments and guidance. The members of the panel of experts and the dates of the emails sent are the following:

- Natalie Carroll, Agricultural and Biological Engineering, Purdue University → 03/06/2014
- Cary Mitchell, Horticulture, Purdue University → 03/04/2014
- Vincent Bralts, Agricultural and Biological Engineering, Purdue University → 02/24/2014
- Louis Albright, Biological and Environmental Engineering, Cornell University → 03/02/2014

What was asked to the panel of experts was to review the Analysis of the thesis. The author first sent the chapter 4 of the Analysis but for a correct review of the analysis the panel of experts also needed to see the assumptions, limitations and delimitations, so the whole thesis was sent to each of the members. What was asked was:

- Review the content of the thesis in both technical and grammatical aspects with special emphasis in the chapter of the analysis.
- Review and check the calculations made.
- Give feedback with comments and corrections when possible.

- Summary of the feedback received person by person:

- Natalie Carroll:
  - Grammar and wording corrections,
  - Add references in text that were missing,
  - Formatting issues, add to section 4.4 explanation of how the location of the vertical farming has been done.
- Louis Albright:
  - Grammar and wording corrections,
  - Add references in text and formatting in the references sections as well.
  - Make some pictures bigger to be easier to read,
  - Adding new assumptions: assuming lettuce without subspecies or varieties.
  - Adding new delimitations: the assumption mentioned above means that the results can change if compared with one specific variety of lettuce or other, so it may not be applicable to all the varieties.
  - Adding new limitations: the limitations that an entirely enclosed facility would have in the air change to keep the concentration of CO_2 under toxic levels, as well as the control of the humidity.
  - Adding disadvantages list to the LED lighting.
  - Added light types for photosynthetic lighting, from the University of Technology, Sweden, in the section 2.4.3.
  - Added some critiques to figure 2.5.

- Modification of the assumption of why the author has chosen Indiana despite that Indiana has not real problems of availability of horizontal space, or accessibility to water.
- Added recommendations for further research.
- Professor Albright sent an energy report from Cornell University as extra literature review for this thesis.
- Suggestion that the 10 story vertical farm can use the tenth floor as a regular greenhouse using natural lighting. This assumption has been included and all the calculations of energy and emissions related to the consumption of kWh hour has changed. Instead of calculating it for 10 floors the author has calculated the use of supplemental lighting for 9 of the 10 floors assuming that the last floor receives sunlight ergo does not consume energy and either produces greenhouse gases.
- Explain what the X and Y/axis from the appendices K to T mean.

- Vincent Bralts:
  - Correction of the calculations in the estimation of yield.
  - Correction of the estimation of water saved.
  - Provided new references.
  - Suggested to include the new water footprint estimation.
  - Verification of the changes done.

Unfortunately not all the members of the panel of experts have been able to give me feedback for several reasons.

2.6 Summary

This chapter summarizes the existing literature on Vertical Farming, urban farming and controlled environments, as well as the methods used, by the experts in these different fields, to develop with the best possible performance the production of food.

The chapter also covers widely the background of the social, economic and environmental factors and goings on around the globe that affects the food production. This serves as strong base, reason and motivation for the researcher to build this study.

CHAPTER 3. METHODOLOGY

This chapter covered the research framework, analysis methods and testing methodology used in this thesis.

3.1 Framework

This is an innovative field of research. There have been few preliminary studies about vertical farming and vertical agriculture. Due to the relative newness of this area of farming, the research done by the author has found there are not an abundance of specific studies in the area of interest of this thesis. The researcher realized that vertical farming is an idea that integrates several ideas and different varied disciplines, such as the ones mentioned in sections 2.1, the figure 2.2 and 3.2 of this thesis.

A priori it seems that the idea of the vertical farm could solve a lot of the actual problems surrounding food production. So the questions are: Why are there not more working vertical farms or vertical farm projects on the horizon? Is it really a good investment? Is it profitable? Is there a possible reality of vertical farming feasible in third world countries or will it remain only available to a few rich countries? The reason that the author has become involved in this project is that there is no clear and unanimous response by the scientific community concerning the action that should be taken with the problem of food security production. The political agenda is full of ecological programs, sustainable construction, efficiency and energy savings ideas, electric vehicles, etc. but as for sustainable food production there is no a clear path that has been established and accepted by the majority. This study did intend to give significant evidence in order to answer those questions.

3.2 Steps of Procedure Graph

- Estimation of schedule agenda
  - Start Spring 2013 - Reading of books and online academic materials to decide Research Question

- Review of the literature
  - Conference proceedings
  - Books
  - Academic articles
  - Interviews with professors and other experts in the area

- Development of proposal
  - Determination factors as location and crops
  - Proof of concept
  - Results and numbers in terms enegy consumption, water consumption, and amount of biomass produced per unit of energy.

- Analysis of information
  - Determination factors as location and crops
  - Proof of concept
  - Results and numbers in terms enegy consumption, water consumption, and amount of biomass produced per unit of energy.

- Develop of conclusions
  - Proof of concept analysis in the whole process of food production, specifically lettuce and leafy greens.
  - Validation of the literature through comparison of several experiments done by Research Institution and Commercial facilities.
  - The validation process of the analysis of this thesis will be held by a panel of experts through cyclical meetings.
  - Extraction of the data from the literature review to calculate light, and water requirements for the indoor growing of lettuce.
  - Calculation energy & water costs for the vertical farm products.
  - Use of the data extracted from the analysis to develop an estimate of produce, for a location determined with ArcGIS software, and see if it could become a reasonable suplement or replacement to mass produced lettuce in terms of energy and water, and considering the environmental impact in GHG.

3.3 Research Approach and Hypotheses

This thesis is a quantitative analysis, and its purpose was to investigate the feasibility of a vertical farm project in a third world country.

The author based his research in previous studies and actual businesses working in vertical farming, indoor growing plants, LED lighting, aeroponics and hydroponics fields.

The hypotheses of the thesis are that the vertical farm is feasible in the location "X" of the state of Indiana, and that the economic factor is not an issue. The variables involved in the analysis are:

A. Independent variables:

   A. The type of lighting used for the plant development and its energy efficiency.

   B. Techniques of water transportation & Technologies involved to create and to manage the control environment.

   C. The most efficient use of space and design of the green house (out of scope).

   D. Cost of the land (out of scope).

   E. Local policies (out of scope).

B. Dependent variables:

   F. Cost building -- How many stories in the building (out of scope).

   G. The kind of crop.

3.4 Data Collection Methods

The methods used to obtain the information necessary to do the analysis (3.3) are:

- Content Analysis: The author has mainly used journal articles, conference proceedings, governmental sources of information, such us the Environmental Protection Agency (EPA) website, Agricultural Statistics, Cornell University, and University of Arizona, among others.
- Interviews between professors of Universities around the U.S and the rest of the world, as well as professionals in the field with practical experience (via email and/or face to face).
- Surveying: The author has found most of the useful information from: Blog (Weblog) and video blog post, online lecture notes and presentation slides, scientific journals, conference proceedings, technical reports, and books.
- ArcGIS software: The author has used this software to locate the most suitable place to build a Vertical Farm. The author defined the parameters in the software through informatics models. The data was provided by the online service Indianamap, TIGER census, census.gov, and template maps of ArcGIS.

3.5 Systems Model of Farming

The author described in this section of the study the systems model of vertical farming. This consist in the identification and description of the different processes involved when running a hypothetical vertical farm, as well as its inputs, outputs and externalities.

It is displayed in the figure 3.1 below the general scheme of what this section is going to talk about.

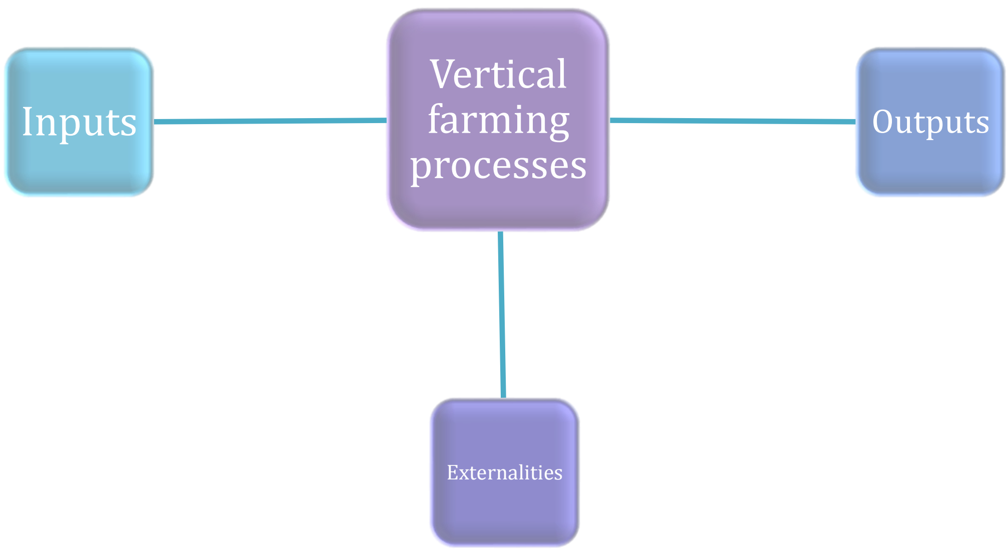

Figure 3.1 General scheme of the vertical farm facility with, (1) Inputs; (2) Outputs; (3) Operational processes involved; and (4) Externalities.

Then the inputs of the hypothetical vertical farm are shown in the figure 3.2, which include: (1) the local legislation, the investors must know if it is legal built such a facility in the area; (2) The cost of the land is another factor that will influence when choosing the location; (3) Designing the facility as well as the controlling systems is the job of the engineers involved in the project; (4) Energy input is the center of focus of the study, specifically the energy of the artificial lighting, but energy also affects the environmental control (heating/cooling), pumping/irrigation, and the nutrient delivery system; (5)Labor; and (6) amount of water that the vertical farm will consume, which is the other major point of study of this thesis.

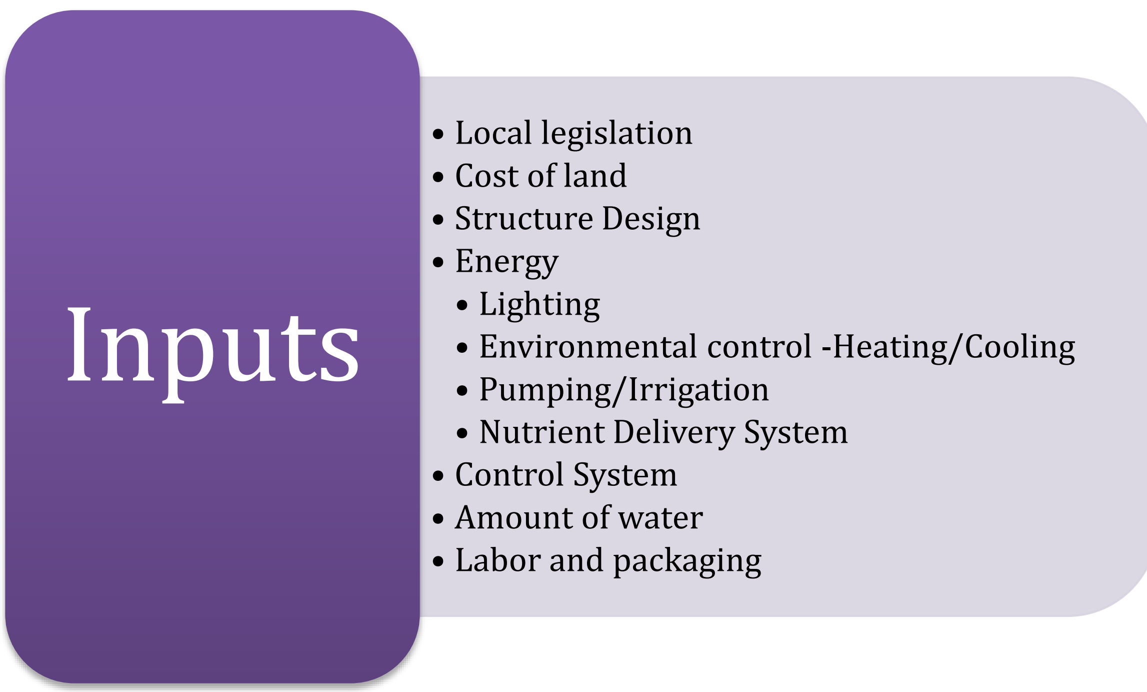

Figure 3.2 Inputs needed for the correct and complete operation of the vertical farm.

The results of running the vertical farm are the following outputs, shown in the figure 3.3, (1) amount of product, in this particular case will be lettuce that is produced by unit of energy and water; (2) the nutritional content and flavor of this lettuce, which is out of the scope of this study but the author has cited in prior chapters; and (3) wastes, in this case because is lettuce the product (there are almost no wastes because practically all the plant is eatable) the wastes will be roots and sick or lettuces with defects that cannot be sold.

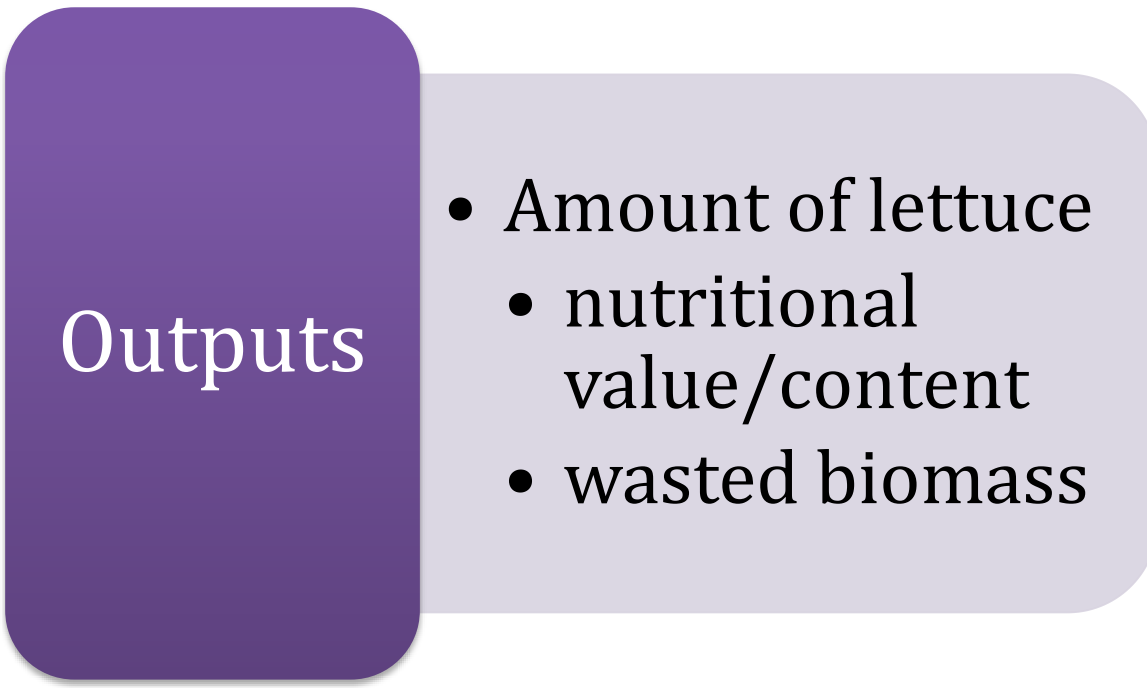

Figure 3.3 Outputs result of the operation of the vertical farm.

The processes involved in the production of food in a controlled environment such as this hypothetical vertical farm are shown in the figure 3.4 below, (1) Type of production system, which will be either hydroponically, which have been described in prior chapters, aeroponically and/or involving aquaponics; (2) when controlling the systems of production it is necessary to consider if the vertical farm is going to be 100% run by artificial lighting, or is going to be a mixt of natural light with artificial lighting. These considerations are also involved in the design process of the facility (inputs).

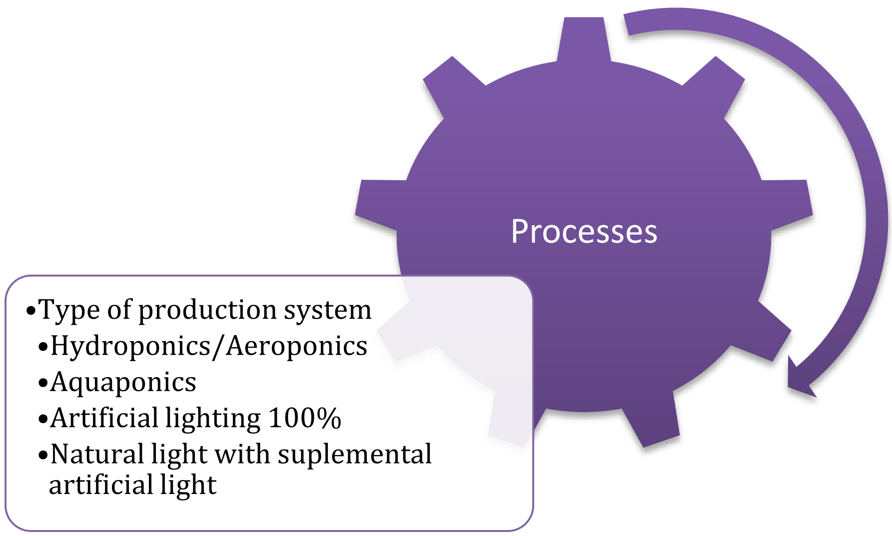

Figure 3.4 Processes involved in the operation of the vertical farm.

The externalities are those defined as "third party (or spill-over) effects arising from the production and/or consumption of goods and services for which no appropriate compensation is paid" Caplan, B. (2008). *The concise encyclopedia of economics*, such as greenhouses gas emissions (or any environmental impact with no compensation paid), or social impacts such as un/employment created…etc. are shown in the figure 3.5 below.

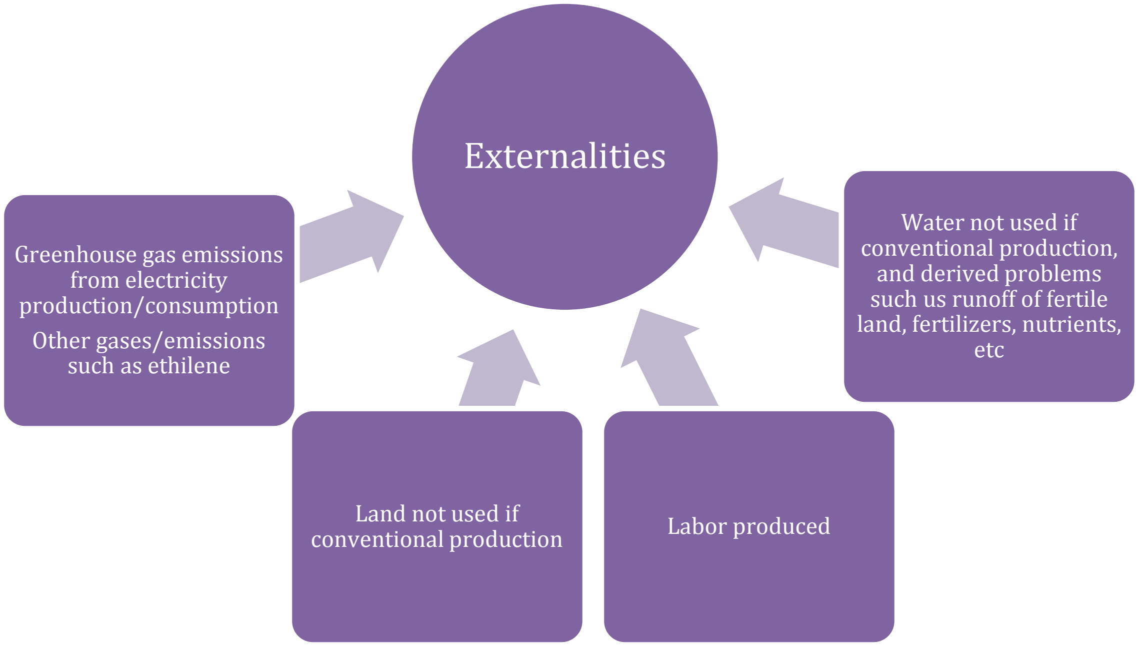

Figure 3.5 Externalities involved in the hypothetical vertical farm.

3.6 Data Analysis

The researcher has made a proof of concept of different business strategies and models that already exist in the world, some of them in the Chicago area. The study has been developed through the analysis of the results of different studies conducted in different educational centers and commercially viable facilities. The numbers used are based on those already mentioned in the literature review. They are based on the worst-case scenario. The reason that the researcher of this thesis has decided to do that is to give a try as realistic results possible. Although the constraints, limitations and assumptions that have been made could give too unrealistic or too optimistic results.

That is, regardless of any factor more than the energy and the amount of water used in the vertical farm, if the worst scenario possible the result is positive, it is encouraging for future research to include more factors than by restrictions time of this study the researcher had to exclude.

The testing methodology that the author used is a comparison among the different models that are being used in real life that appear in the review of the literature. The results acquired showed the most optimal rate investment in terms of money and/or energy and water, and the biomass produced (lettuce). From the different systems the author tried to obtain the results for worst-case scenario. For each analysis or data interpretation done, the author has assumed that the systems are equivalent in size, demand of product, price base of materials, water and energy, to come up with some final numbers to work with and develop and estimation of energy and water required for the location 'X', of population 'Y', that consumes 'Z tn/lettuce per person/year' and how much produce can be generated to satisfy this demand. It is reasonable in terms of energy and water to replace all the lettuce produced by mass production for vertical farm produced? It is more reasonable to become a supplement than a replacement?

3.7 Summary

This chapter covers the key variables in the study, and the samples that need to be tested and compared. It also describes what data was used and how the testing framework is setup.

CHAPTER 4. ANALYSIS

In this chapter the author presented and described the data. As mentioned in the prior chapters, the purpose of this study was to make the reader aware of the contemporary problems that exist around the food production, energy and water shortages and environmental problems derived from human action. Also, analyze the background and previous studies and findings in the area of vertical farming, indoor food production or controlled environments, and how these different perspectives have similar ways to focus the problem. This thesis is the attempt to answer the following questions "Is it feasible to replace mass produced lettuce outdoors with locally grown lettuce utilizing Vertical Farm (VF) methods?" The central questions of this thesis were (1) Where should a Vertical Farm (VF) be built in an urban or suburban environment within the state of Indiana?; (2) What is the relative demand of energy of lettuce production in a vertical farm or controlled environment to provide lettuce for the location 'X'?; and (3) What is the relative demand of water of lettuce production in a vertical farm or controlled environment to provide lettuce for the location 'X'?

Books, interactive media, video-conferences and conference proceedings, thesis research and scientific articles were used as reliable base for the statement of the problem and to narrow down the scope and development of the research questions that will be analyzed in this chapter. Additional data sources included observational analysis directly from greenhouses, and interviews face-to-face or via email with experts in the fields involved in this study.

This chapter presents the data of the most recent individual findings and research of multiple investigators and entrepreneurs around the globe. It begins with the energy parameter, (1) choosing the artificial lighting; and followed by (2) an energy cost analysis of this chosen lighting technology. This is followed by (3) the analysis of the water consumption through the hydroponic systems mentioned in prior chapters. The analysis chapter will also treat (4) the amount of lettuce produced with a vertical farm of these characteristics and (5) the greenhouse gas emissions, in CO_2, derived from the energy consumption.

The chapter then provides the findings related to energy and water consumption for lettuce production and its effects in the population 'X' chosen as well as the environment, as well as a quick estimation of land efficiency and the summary.

4.1 Energy analysis

In this part of the chapter the author will explore in detail the consumption of energy based in the most relevant and actual data cited previously in the chapter of the literature review.

The author showed some of the literature review existing towards vertical farm and the energy inputs that require growing crops in an indoor control environment. The analysis will address what kind of source of energy is used, how much energy, where this energy is used, and to produce how much product.

4.1.1 Choosing the artificial light source

One study done in Purdue University was focused in *Comparing LED Lighting To High-Pressure Sodium Lamps*. The study showed that there was a slight increase in the root and shoot dry weight for petunia cuttings rooted under the LED lights, while stem length was also slightly shorter. However, while these differences were statistically significant, they didn't find the results to have much commercial significance since the differences were so small. Some LED manufacturers have claimed light from LEDs will result in an increase in photosynthesis, but the study done by Christopher J. Currey and Roberto G. Lopez found nothing that would support this claim, as well as unpublished data at Cornell, in words of prof. Albright comparing T12, T5 and LEDs found no differences when the DLI was held to be the same. As both said " the only significant effects observed were a slightly greater stem length and dry mass for petunias grown from cuttings propagated under 85:15 red:blue light when compared to plants finished from cuttings propagated under HPS lamps. Again, while statistically significant, they have little impact or commercial significance." Currey, J. C., and Lopez, R. G. (2013), 3.

The study of Christopher J. Currey and Roberto G. Lopez also focused in quantifying the effects of LEDs on the growth and flowering of cuttings, the researchers wanted to assess the energy use of the different supplemental lights.

> "The daily energy consumption of the HPS, and 100:0, 85:15, or 70:30 red:blue LEDs was 3.01, 3.29, 3.43, and 4.06 kWh•d-1, respectively. Blue light (450 nm) is a higher-energy light compared to red (635 nm), causing an increase in energy consumption with an increasing percentage of blue light. Additionally, while LEDs do not produce radiant heat with the light that is emitted, there is heat generated by the diode itself. In order to maximize the long lifespan of LEDs, the heat must be removed from the diode and this can be achieved passively, with a material that would act as a heat sink, or actively with the use of air-cooling. Although the LEDs consumed more energy, the fans used to air-cool the arrays consumed 1.49 kWh per day and accounted for 37 to 45 percent of the total energy consumption for each LED array. Using a passive heat sink would reduce the energy use and, therefore, operating costs of the LED lights. However, a passive heat sink would also likely increase the size of the fixtures and initial investment cost."
> (Christopher J. Currey & Roberto G. Lopez, 2013, p.3-4)

Thought their study is not based on lettuce, the findings of their research are supported by other researchers with similar findings.

Other articles have been included in the analysis in order to set solid bases of a valid and reliable conclusion when choosing the most energy efficient source of artificial light to grow lettuce indoor. The article *Problems with Foot-candles, Lux and Lumen, 2013* says that blue and red LEDs are most often used for plant lighting because:

1. They are the most energy-efficient colors of LEDs. But the efficiency depends on wavelength so anything longer than blue will be more efficient than blue. So, according to prof. Albright the LEDs made at these wavelengths were among the

earliest made and so have had longer development times – leading to more efficient units.

2. They are considered to be more photosynthetically efficient than green or white light.

3. The addition of 10 to 20 percent blue light to red light produces a more "normal" plant shape; most plants grown under only red light are elongated.

And it also compares it with other types of light sources, see figure 4.1 below.

Light source	Photon efficiency ($\mu mol \cdot J^{-1}$)	Luminous efficiency ($lm \cdot W^{-1}$)
Cool-white fluorescent	1.2	90
High-pressure sodium	1.6	130
Blue LEDs (peak=455 nm)	1.8	47
Red LEDs (peak=655 nm)	1.7	17

Figure 4.1 Comparison of the photosynthetic photon efficiency (for plants) and the luminous efficiency (for people) of four light sources. Metrics based on lumens (lux and foot-candles) are highly misleading and inappropriate for plant applications. (Runkle, E., & Bugbee, B., 2013, p.78)

During the analysis to choose the best and more efficient source of artificial light for growing lettuce the author has identified that there are three ways to describe light intensity, but only one of them is appropriate for photosynthesis. Increasing use of light emitting diodes (LEDs) means that the appropriate unit for light measurement is more important than ever. Although light quality and timing are powerful tools for altering plant shape, light intensity provides the horsepower to drive photosynthesis.

- **Photometric: Foot-candles and lux.** These units of measurement are based on the perceived brightness to the human eye. Our eyes perceive green and yellow light much better than blue or red light, so this measurement system is completely biased toward people and is not appropriate for plants. Since most lighting applications are for people, this system is used by lighting professionals and utility companies, who usually optimize lighting for people. Therefore, the efficiency of lamps is almost always reported as the luminous efficacy, which is the number of lumens per watt of energy. (One lumen per square meter equals one lux, and there are 10.8 lux per foot-candle.) (Runkle, E., & Bugbee, B., 2013, p.78)

- **Radiometric: Watts.** This unit is used to determine the energy input and output of lighting applications. It describes the power of light that a light source emits or consumes. The light energy increases as wavelength decreases, so it takes more energy to make blue light than red light. Thus, this measurement system is based on power and is used to predict the heating value of light. It is not specific to plants or people. (Runkle, E., & Bugbee, B., 2013, p.78)

- **Quantum: Moles of photons.** The Stark-Einstein Law tells us that one photon excites one electron in photosynthesis, regardless of color, so counting photons is the best way to predict photosynthesis. The number of photons in the photosynthetic waveband (400 to 700 nm) is typically reported as micromoles per square meter and second, or $\mu mol/m^2/s$. This system considers all colors of light equally and is the most appropriate way to measure light intensity for photosynthesis and plant growth. (Runkle, E., & Bugbee, B., 2013, p.78)

Measuring moles of photons is not biased toward human vision; in fact, an intensity of deep blue and deep red light that appears dim to us can be bright light for plants.

After seeing the table and definitions given by Erik Runkle and Bruce Bugbee, 2013 in the article *Problems with Foot-candles, Lux and Lumens*, the blue and red LED rise as the more efficient plant lighting (based on photons and not lumens.).

The same way, the articles *LEDs Lower Costs, Boost Crops Inside Greenhouse*. June 2012 by Lynn Savage, the researcher Erick S. Runkle says that the light-intensity range required for boosting plant growth depends upon the location, time of year, crop, temperature and CO_2 content in the air surrounding the plants and given those vagaries, the common light intensities used to increase photosynthesis range from 50 to 200 μmol/m^2/s – or approximately 4,100 to 16,400 lx from high-pressure sodium lamps. The researchers of the article as well as horticulturists coincide in measuring the intensity in molar units rather than lux because the latter is defined by how light is perceived by human vision (p.2)

The author found more evidences of the advantages of LEDs among the other sources of artificial light, such as in the article *Making LEDs Easier to Choose and Use. June 2013*, and *LEDs: The Future of Greenhouse Lighting!* by Cary A. Mitchell, Arend-Jan Both, C. Michael Bourget, John F. Burr, Chieri Kubota, Roberto G. Lopez, Robert C. Morrow and Erik S. Runkle, among other articles that the author is not going to go in depth for this analysis, coincides with the article *Problems with Foot-candles, Lux and Lumen, 2013, and LEDs Lower Costs, Boost Crops Inside Greenhouse*. June 2012, among other articles, saying that LED is the most optimal option of artificial source of light for growing crops, and supports the idea of the researcher of the present thesis in the use of LEDs as artificial source of light. In words of Both A.J., Rutgers University "LEDs offer the potential to reduce electricity consumption while maintaining or even improving plant growth and development."

So, as final conclusion for this part of the analysis and based in the previous articles that supports the choice of LED that the author of the present thesis has arrived to the conclusion that LED are the best source of artificial lighting for growing lettuce in the hypothetical vertical farm of this study, with the following advantages:

Advantages of LEDs in Greenhouses

- Lower heat output, permitting proximity to plants
- Highly selectable wavelengths
- Lower cost of use
- Longer life than incandescent lighting
- Compact device size
- Flexible design options for horizontal or vertical lighting and for moving fixtures
- Potentially higher quantum efficiency
- Unlike with incandescent lamps, proximity of LEDs to leaves and stems does not cause burning or dehydration of plants, neither is the meristem tissue warmed, so there may be need to raise air temperature to compensate.

Disadvantages of LEDs in Greenhouses

- High initial cost. As the technology develops, the lights should become cheaper. The lights will save more money than sodium or halide lights in the long run.
- Light replacement. Traditional growing lights let the user replace the entire bulb if one light goes out. This does not happen with LED lights. If enough bulbs on a strip go out, the user has to replace the entire unit.
- Heat Sink. LED lights need to have a good heat sink. Otherwise, the LED chips can overheat and break. Check that the light you purchase has a good heat sink with many fins and a good fan.

4.1.2 Cost of energy

This section will talk in detail about the energy consumption of the artificial lighting (LED) used in the hypothetical vertical farm and other uses such us dehumidifiers and pumping the water.

4.1.2.1 Energy cost of lighting

Paraphrasing Professor Louis Albright from Cornell University in his UK International Greenhouse Conference of 2012, he used an engineering analysis process "first, examining the claim that crops such as wheat are possible and farmland can be returned to its primordial state.

Economic viability of CEA wheat production is one metric that comes to mind.

The world record for outdoor wheat production was set in 2010 in New Zealand with 1.567 kg m^{-2}"

The next data from *Finger Lakes Fresh* show some estimations of cost of electricity in lighting for the production of wheat, and lettuce, being this last crop especially important in the present thesis. This data is used in the engineering analysis done by prof. Louis Albright, a skeptic on the vertical farm idea and the suitability of growing food with artificial light from Cornell University. The present thesis is including the comments, conclusions and numbers of his analysis as valid source of information to answer the research questions. The analysis starts comparing the best scenario possible of wheat production with conventional farming compared with the same crop under artificial light in a production chamber or controlled environment. The numbers are shown in the figure 4.2 below.

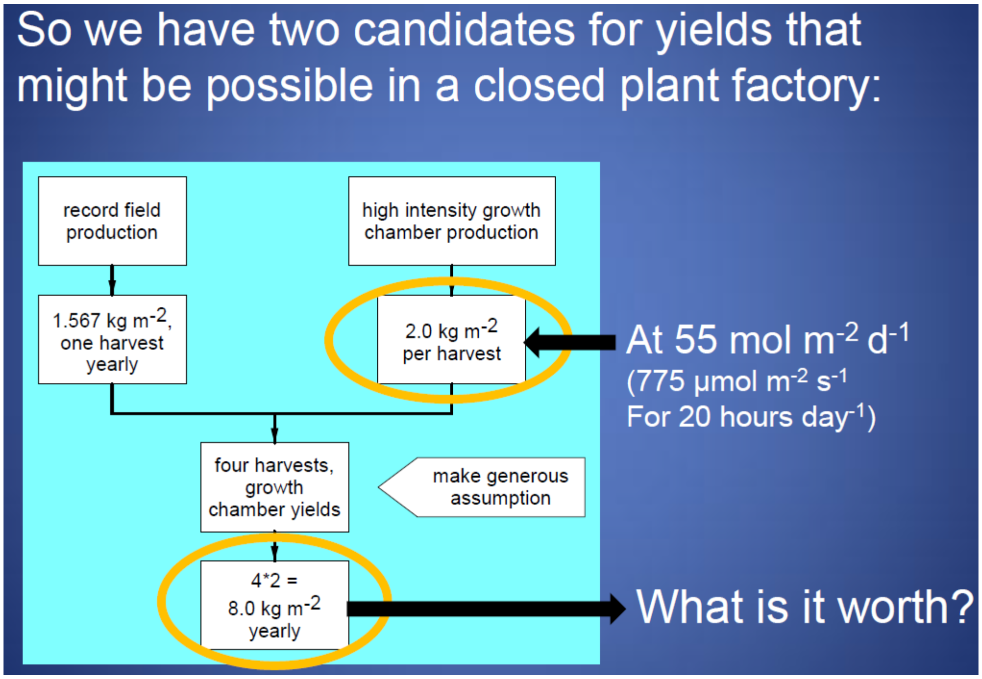

Figure 4.2 Amount of biomass of wheat in kilograms per unit of area (meter square) produced by conventional farming versus controlled environment (Albright, 2012, p.13)

In order to know the economic feasibility of this project it is key factor to know the prices of wheat per kilogram.

Table 4.1 Examples of wheat prices (World Bank, 2012)

Month	$/metric ton	$/kg
Dec 2011	269	0.269
Jan 2012	275	0.275
Feb 2012	278	0.278
Mar 2012	284	0.284
Apr 2012	266	0.266

Average value ($) per kg of wheat = 0.275

To know how much is worth, the calculations are made with the number of crops that are four in the year with a production of 2kg of wheat/m^2, it means that this harvest times four gives us a hypothetical yield of 8kg of wheat/m^2. Following prof. Albright calculation of Gross Yearly Income, taking the average cost per kg of wheat and multiplied per 8kg as hypothetical yield of the controlled environment results in; ($0.275 kg^{-1})(8.0 kg m^{-2} year $^{-1}$)= $2.20 m^{-2} year $^{-1}$, and this is gross income.

The conclusion is that any crop considered must be much more valuable than any commodity. Corn, wheat, etc., cannot be possible crops. The income is one perspective. Cost is another. What is the cost of just the electricity to run the lights to grow the wheat? The study assumes efficient lighting: HPS or good LEDs, with income $2.20 m^{-2}; what is the electricity bill? Professor Albright makes this specific question as example; what will be the electricity cost of a loaf of bread if the wheat is grown using only electrically generated light?

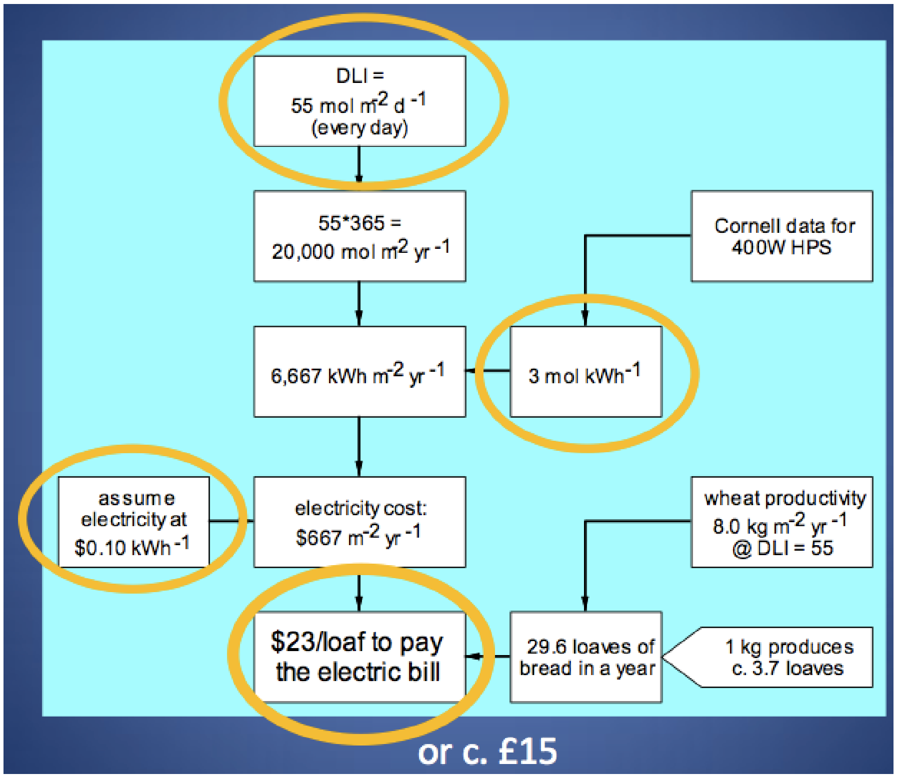

Figure 4.3 Estimation of the electric bill of growing wheat to produce a loaf of bread with supplemental lighting (Albright, 2012, p.18)

The results showed that commodities will not pay, so Professor Albright showed as Model for discussion the CEA lettuce greenhouse near Ithaca now operated by Challenge Industries as "*Finger Lakes Fresh*" (FLF), which model is of relevance for this thesis. *Finger Lakes Fresh* demonstrated productivity is:

Production capacity is 1245 heads/day

Equal to 760 heads/m^2*year

What the author of the thesis wanted to show with the figure 4.4 below is a comparative made by *Finger Lakes Fresh* where it is shown the difference in energy consumption between lettuce production with a 30% of supplemental (artificial) light and 70% natural light and lettuce production with 100% supplemental (artificial) light.

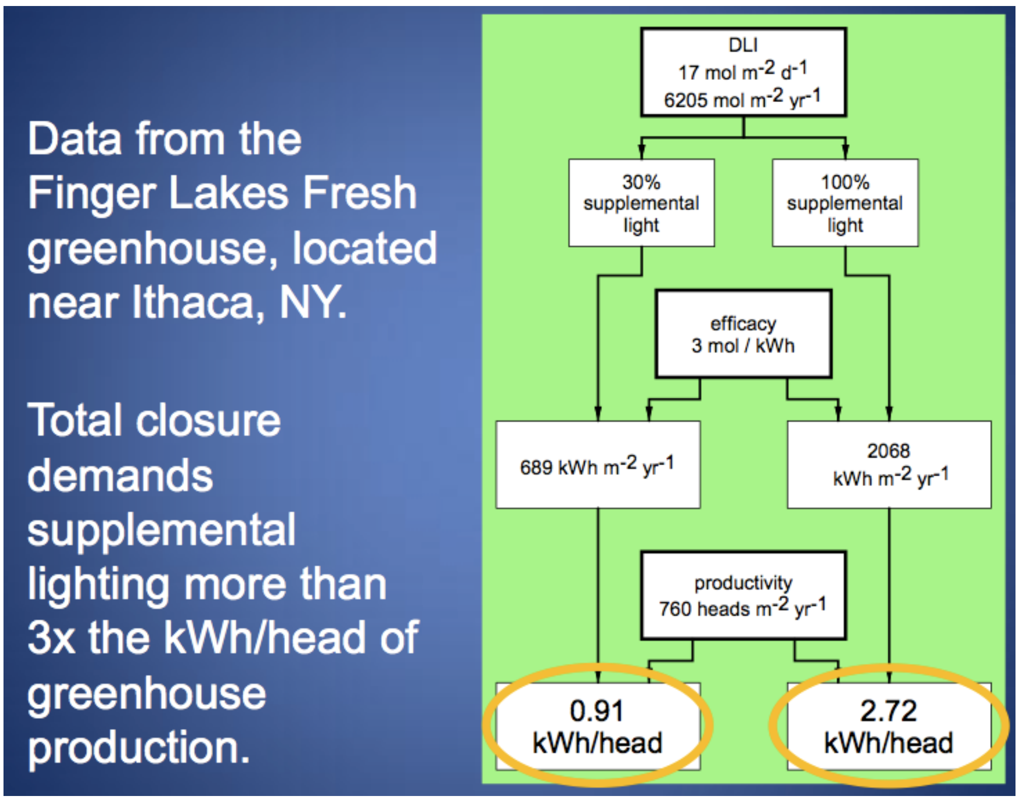

Figure 4.4 Demand of energy consumption between 30% supplemental light and 100% supplemental light. (Albright, 2012, p.21)

According to Professor Albright conclusions from this data "the hydroponic vegetable production is already marginal in many situations. Adding the cost of more than three times the kWh per head of lettuce, for example, seems not viable economically today, or in the foreseeable future.

LED technologies are improving and their costs are shrinking. However, claims that today's commercial LEDs are much more efficient are not justified by data. Current LED arrays are typically compared to incandescent lamps, which are notoriously inefficient. HID luminaires and T5 fluorescent fixtures are also much more efficient than incandescent bulbs, with efficiencies approaching the best LEDs." (Albright, 2012, p.25)

Professor Louis Albright makes the next question, what is the carbon footprint associated with obtaining sufficient light to grow a food crop with 100% supplemental light? But what he did not consider in his work was the actual footprint of the conventional farming, and if that is sustainable or not. This would be an interesting area for further research that the author is not going to do in the present thesis, but it will be commented in the suggestion and recommendations in the following chapters of the thesis. Professor Albright did not consider either the cost of water and the savings of water either, nor the environmental impacts that conventional farming are doing to the aquifer ecosystem, rivers, lakes, and oceans as well as all the problems involved with erosion, loss of fertile soil and runoff, runoff not of soil but also of pesticides and fertilizers that go downstream. What his study did show was the greenhouse gas emissions (CO_2) from 100% supplemental light per head of lettuce produced. Figure *4.5* below shows the equivalence in grams of CO_2 per kWh of energy produced; these numbers have direct relation with the production of lettuce.

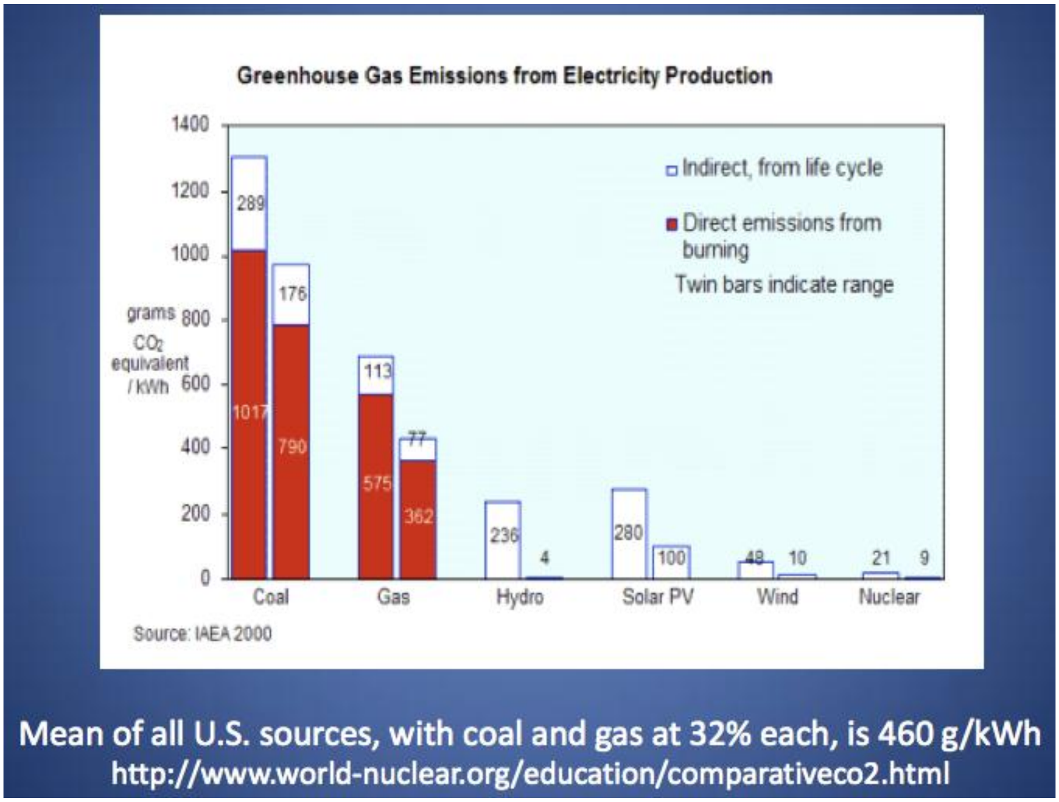

Figure 4.5 Equivalence of greenhouse gas emission from electricity production per combustible. (World Nuclear Association, WNA Report, 2012)

In this thesis the objective is to provide 100% supplemental (artificial) light. Assuming the estimations of productivity of Cornell University by Professor Albright, it is possible to assume a productivity of 760 heads of lettuce/m^2/year, where each head weights approximately between 150 and 160 grams. With these two numbers it is possible to calculate the yearly lettuce mass produce by meter square, which will be 118 kilograms. With 100% artificial light the energy consumed is 2068 kWh/m^2/year, so (2068 kWh/m^2/year) / (118 kg/m^2/year) = **17.5 kWh/kg of lettuce.**

Following the estimations done in the section 4.3 the author has found that the vertical farm can produce 8,481,600 kg of lettuce x 17.5 kwh/kg lettuce = **148,428,000 kWh** is the total value of energy of a 100% artificial lighting vertical farm of 100m x 100m x 10 story. The production numbers of Cornell University but, are based on floating raft growing, which would be heavy to support. Other systems would likely be less productive, due in part to the ability to re-space and make good use of space in a pond system.

After the consideration of the comments of professor Albright, the author of this thesis has reassumed the design the vertical farm to reduce the amount of energy consumed by amount of lettuce produced. The assumption is the following; if the vertical farm is a facility of 10-story building, the 10th floor could use natural light and work as a regular greenhouse with controlled environmental. Under that new consideration the energy consumed by the 9 stories with supplemental lighting is **133,585,200 kWh**.

4.1.2.2 Energy of Internal Environmental Control

This section will mention quickly some of the environmental control processes and technologies involved in the functioning of the vertical farm. Even being out of the scope of the thesis, the author has considered it important enough to dedicate this sub-chapter.

In first place it is necessary to name those major building systems that need to be studied in further research. Those include internal temperature control (it could be with geothermal heat pump), an air handling system for ventilation, and industrial dehumidifiers, when providing energy to the facility and using the organic matter wasted it could include anaerobic digesters tanks and biogas-fuelled generators.

4.2 Water analysis

In this section of the thesis the author is going to study the amount of water involved in the cycle of growing the lettuce in the enclosed system. Based in estimations of evapotranspiration in the life cycle of the lettuce the author will determine the amount of water that needs to be added and the amount that can be recirculated through dehumidifiers. According to Toyoki Kozai, Chief Director of NPO Japan plant factory association, in dehumidifying the air plus recirculating the water using hydroponics or aeroponics, we reach the 97% of water use efficiency compared with the conventional farming. Kozai, T. (2012) p.21. The author will also include the amount of water needed per plant in order to determine how much water the vertical farm consumes.

4.2.1 Cost of water

In the analysis of the cost of water the author will consider the water needed to grow a head of lettuce and make estimations for the whole vertical farm, as well as the water evaporated through the process of respiration of the lettuce.

Taking the data from Mekonnen, M.M. and Hoekstra, A.Y. (2011) *The green, blue and grey water footprint of crops and derived crop products*, the global average water footprint of lettuce is 240 liter/kg. "However, the water footprint is different from place to place.

For example in China and the USA, the two largest producing countries, lettuce has a water footprint of 290 and 110 liter/kg, respectively." (waterfootprint.org, 2011) retrieved from http://www.waterfootprint.org/?page=files/productgallery

After calculating the amount of lettuce produced by year, the next step is to estimate the amount of water required by the vertical farm to keep this level of production. Taking 8,481,600kg of lettuce/year, calculated in section 4.3, this amount evaporates through the transpiration of the lettuce 15,491.47 l H_2O per day or x 365 days, 5,654,386.55 l H_2O per year. Considering the global average water footprint of 237 l H_2O/kg of lettuce, the calculations water requirements will be done with the amount of lettuce (weight) multiplied by the volume of water needed to produce this lettuce (it has been taken the world average instead of only the State of Indiana . As it follows, 8,481,600kg of lettuce/year * 237 l H_2O/kg lettuce = 2,010,139,200 l H_2O/year. That's the total volume of water needed to grow the lettuce under conventional farming. Because the vertical farm has controlled environment, through dehumidifiers the water evapotranspirated is recirculated and also hydroponic recirculating systems, preventing loses of water from the system. The author has assumed then, that the total water needed under conventional farming, which is 2,010,139,200 l H_2O/year, exceeds by 97% the water that the vertical farm would need. In other words, the water use efficiency of this hypothetical vertical farm will be of the 97%, which means that the vertical farm will be using only the 3% of the water that is used in conventional crop due to the controlled environment. Considering the assumption that the lettuce is evapotranspiring all the time, and the same amount.

The cost of water of the vertical farm of this characteristics will be 2,010,139,200 l H_2O/year – 97% of the H_2O = **60,304,176 l H_2O/year**, or 60,304.17 ton H_2O/year, or in US units **15,930,677.94 gallons of water/year,** knowing that 1 liter is 0.264172 US gallons.

- The new water footprint will be 60,304,176 l H_20 per year/ 8,481,600kg lettuce per year = 7.11 l H_20/ kg lettuce, which is over 33 times less water than conventional farming. Although it seems small this is consistent with Staghellini, 2011, p.11.

In reference to (Graff, 2011, p.91) to produce the same yield of lettuce (~18 metric tones) a dehumidifier-equipped vertical farm would lose just 14.4 metric tones of water, assuming the standard 80% water content for the weight of lettuce. In other words a vertical farm could produce lettuce while consuming just 0.8% to 0.41% (i.e. 1/240th) of the water needed for conventional lettuce production.

According to program director Dr. Louis Albright the Cornell facility's hydroponic lettuce transpires approximately 1 mm of water per square foot, or 0.093 liters, per plant per day. Using these values in the calculations for the present study, for a maximum daily production of 166,575 heads of lettuce the vertical farm is expected to produce (166,575 heads of lettuce x 0.093 l H_2O/head of lettuce/ day = 15,491.47 l of H_2O) **15,491.47 liters of water per day** through the evapotranspiration of the plants at maturity.

Based in the data provided by the thesis research of architecture *Skyfarming* (Graff, 2011, p.91), this hypothetical vertical farm will need 30-ton DCA 14000T dehumidifiers, sold by the Dehumidifier Corporation of America. This model can remove 170 pounds of water per hour. Considering the estimations of water transpired by the lettuce of 15,491.47 liters of water per day, where 1 liter is 2.2 lbs, then 15,491.47 liters x 2.2 = 34,081.23 lbs of water per day. Each humidifier can remove 170 lbs of water, which means that 34,081.23 lbs / 24hrs = 1,420.05 lbs of water / hour / 170 lbs per dehumidifier = 8.35 dehumidifiers.

To prevent accumulation of water in the air, **the vertical farm will need 9 dehumidifiers** to remove all the water evapotranspirated by the lettuce. The energy cost of dehumidifiers and the cost of installation are beyond scope of this thesis, but the author recommends further research in more energy efficient methods to remove the moisture in the air.

If the vertical farm is equipped with enough dehumidifiers, the water that is evapotranspired by the lettuce will be recirculated into the aeroponic/hydroponic system. With this measure of internal environmental control "the vertical farm would theoretically only lose water hat is needed for plant germination and initial growth and that contained within the sold produce, realizing maximum feasible efficiency of water use for agricultural productivity"(Graff, 2011, p.91).

4.3 Land Efficiency and Lettuce produced

In this section the author is going to quickly estimate the land efficiency production of the hypothetical vertical farm and to calculate the amount of lettuce produced per unit of energy (kWh) and year. The author is going to go a little bit deeper and show the amount of eatable lettuce, which is the amount of lettuce that finally will be able to be consumed.

The author has chosen stacked drums as technique of production because is the technology that has the best land productivity improvement, which is seven times the conventional productivity. (Graff (2011) p.72)

Based in the estimation of the National Science Foundation of 2012 to feed a population of 100,000 people it is needed 1m^2 per person, which means that the vertical farm should be 100m x 100m x 10 layers, of course, considering that the top layer would work as a regular greenhouse.

To estimate the land efficiency the author is going to multiply the usable area of the building's footprint by the number of levels, the growing system productivity factor, and the CEA productivity factor for the lettuce, this last factor will be different for the lettuce.

The following calculations are an approximate estimation of how much land the vertical farm will be using and how much land would have been used if conventionally grown.

Footprint: 100m x 100m = 10,000 m^2

Usable floor per layer: 10,000m^2 – 20% = 8,000m^2, where the 20% is the access/circulation spaces. (Graff, 2011 p.74)

Total floor area: 8,000m^2 x 10= 80,000m^2

Once, the total floor area has been calculated, it is needed to include in the calculation the stacked drums productivity, so the growing area will be 80,000m^2 x 7, (where the seven is the ratio of growing area to footprint of triple-stacked drum design hydroponic system)= 560,000m^2. As mentioned in the chapter two of the literature review, for lettuce, the yield equivalent of Cornell's S/CEA facility mentioned previously is 470 tons per acre per year - over twenty three* times more productive than the typical California lettuce farm's yield for the same land area. (Graff, 2011, p.69). Then the productivity factor is 560,000m^2 x 23* = 12,880,000 m^2, which is approximately 3,182 acres.

The conclusion is that the hypothetical vertical farm of this study could produce the same amount of lettuce as 12,880,000 m^2 of conventional open-field farm. The building of the hypothetical vertical farm of 10,000m^2 of area will produce (12,880,000 / 80,000) = the yield of the building footprint is 161 times than conventional lettuce farm production, and reduce the land required for lettuce production by a factor of (12,880,000 / 10,000) = 1,288.

For the estimation of the amount lettuce (in heads and kilograms) produced the author followed the conservative estimations from Cornell University (Louis Albright, 2012) of 760 heads of lettuce/m^2/year. Other sources of information are using other estimations based in their own experimentation and results, for example from Mirai in Japan is estimating around 1,825 heads/m^2/year of 100 grams per head approximately.

After the analysis of the amount of land the vertical farm the author calculated the amount of lettuce (in kilograms and heads) under the conservative estimations of professor Albright of Cornell University (760heads/m^2/year), with 80,000m^2 of usable surface x 760 heads/m^2/year = 60,800,000 heads lettuce/year (over 60 million). Considering a loss of 10% due to pathogens, disease or physiological anomalies, the number of product useful to be sold will be 60,800,000 x 0.90 = 54,720,000 heads of lettuce. Each head of lettuce weights around 150-160g, so the author will use average of those weights to calculate the kilograms of lettuce per year. 54,720,000 heads of lettuce x 0.155 kg/head of lettuce = **8,481,600 kg or 8,482 ton of lettuce /year produced by the 10 story vertical farm and dimensions of 100mx100m with stacked drums.**

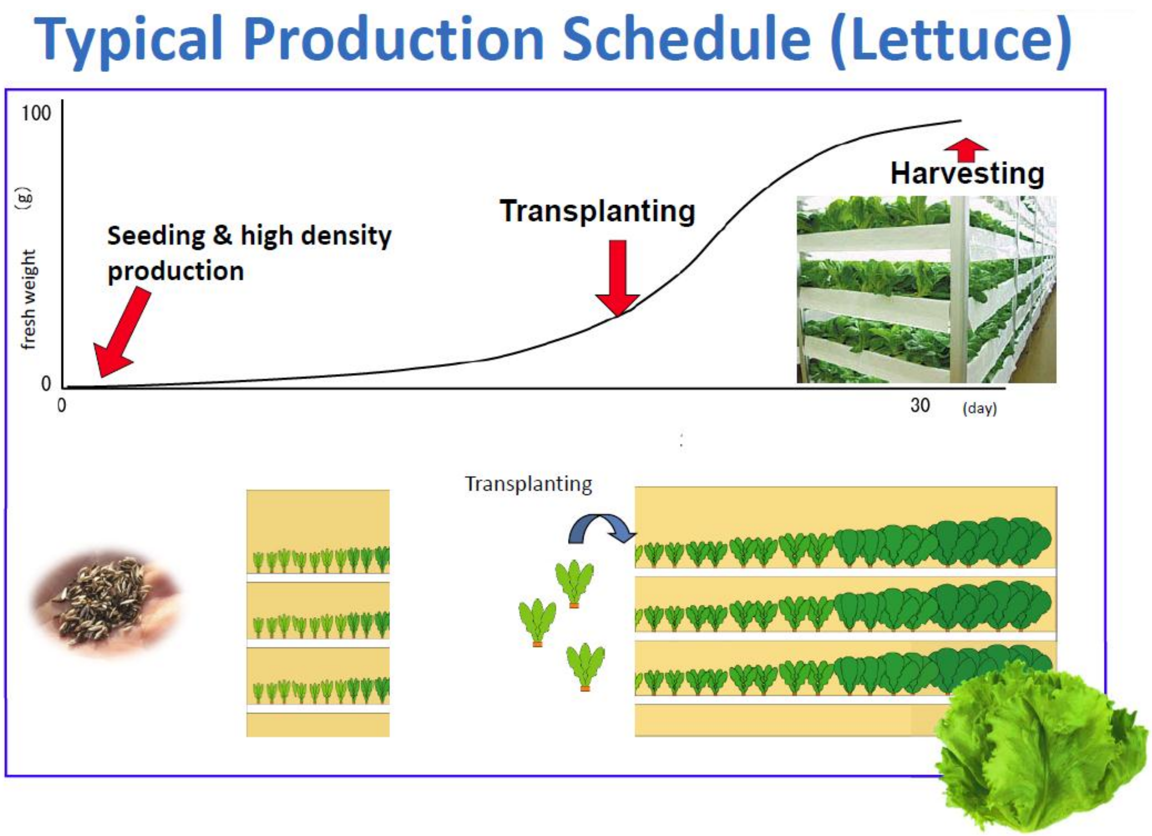

Figure 4.6 Typical Scheme of the life course of the crop in the facility (Shimamura, 2012, p.6).

In this figure the author wanted to show the growing cycle that is done in the vertical farm under the optimal conditions that drives to a growth of the seeds into a mature plants in 28-30 days.

And not only is produced faster, but also according to experimental data from Mirai, the lettuce produced has more harvestable aerial biomass compared to outdoor growing, which reduces the amount of wasted biomass and improves the efficiency. It is showed in the following figure 4.7.

Lettuce produced in GreenRoom™
- 97-98% harvestable aerial biomass
- Waste 2-3 % of biomass

Conventional lettuce head
- 60-70% harvestable aerial biomass
- Waste 30-40% of biomass (outer leaves and center cores)

Figure 4.7 Advantages from Lettuce produced by vertical farming versus Conventional farming (Shimamura, 2012, p.8).

4.4 Location of the Vertical Farm

This section will show the considerations taken by the author in order to build the hypothetical vertical farm.

Where is the location 'X' (where 'X' can be seven different points, see Appendix A, in the State of Indiana, which accomplish the requirements used in the model), amount of population 'Y' (each of the five points in the State of Indiana have more than 100,000 habitants), and this population that consumes 'Z kg/lettuce per person/year' and how much produce can be generated to satisfy this demand.

The steps follow in order to determine the most optimal location for the vertical farm are:

1. Generate a map of the State of Indiana from the database of ArcGIS 10.1
2. Populate the map with all the Brownfields that exist in the State of Indiana.

3. Populate the map with all the Hospitals that exist in the State of Indiana.
4. Populate the map with all the Schools that exist in the State of Indiana.
5. Populate the map with all the Composting facilities that exist in the State of Indiana.
6. Divide the State of Indiana by counties.
7. Using the "*statistics calculator*" tool from ArcGIS to determine the counties with population greater than 100,000 people. Also used to determine in those areas with population greater than 100,000 where a large population of young people resides, considered from under five to 39 years old.
8. Considering only areas that accomplish the point 7 and also have income equal or greater than $50,000.
9. Using the ArcGIS modeling tool the author created a model, see appendices U, V, W and X, to reduce the areas of interest to the final answer, see appendix A. Based on distance of these areas (Brownfields within a large young population and greater than 100,000 people) from schools, composting facilities, and Hospitals but not clinics.

The author has taken the estimations of the Japanese Mirai, which determine that, the daily requirement of fresh vegetables and fruit per person is of 200 grams. So 200g (or 0.20kg) x 100,000 people =

20,000,000g/day/population, which are 20,000kg of fresh vegetables and fruit per population of 100,000 people. To quickly estimate the annual requirements of vegetables per person: 0.20kg/person/day x 365 days = 73kg of fresh vegetables and fruit per person and year.

This amount of 73kg multiplied per 100,000 people = 7,300,000kg or 7,300 tons of vegetables/ Population of 100,000/year.

The hypothetical vertical farm that this thesis is considering in the analysis would produce, as calculated in the section 4.3., an annual yield of 54,720,000 heads of lettuce, with an average weight of 155g or 0.155kg per head is 8,482,600 kg of lettuce/year or 8,482 metric tons. The author of the present thesis has calculated the amount of vegetables needed to provide the 100% of the needs of the population 'X', which is 7,300 tones/year, and the amount of produce that the vertical farm would produce. The results are that the vertical farm would produce a surplus 1,182 tons of lettuce that could be sold in the rest of the county or surrounding populations. These results are based in the assumption that all the requirements of fresh vegetables and fruit are satisfied with lettuce, which is not a real fact, but it fits the assumption that all the production is sold.

4.5 Emissions

According the estimations of Cornell University (Louis Albright, 2012), with a 100% of use of LED as source of artificial light, the energy consumed will be around 17.5kWh/kg lettuce or 2,068 kWh/m^2/year and the levels of emissions will be around 21.6 ft^3 of CO_2/head of lettuce (or 0.62 m^3 of CO_2), as greenhouses gas emissions to the atmosphere.

To quickly estimate the amount of CO_2, or carbon footprint, the author used 8,481,600 kg of lettuce * 0.90, which is the production of the 9 floors that use 100% supplemental light, and subtract the 10th floor because it will work with natural light as a regular greenhouse. If there is 0.62 m^3 of CO_2per head of lettuce and each head is about 0.155 grams, it means that per each kilogram of lettuce we have 6.45 heads. Multiplying 0.62 m^3*6.45heads of lettuce = 4 m^3 CO_2/kg lettuce, and this result multiplied by the density in normal conditions (20C and 1 atm. of pressure), which is 1.842kg of CO_2/m^3 of CO_2= 7.37 kg CO_2/kg lettuce. Finally to obtain the total weight of CO_2 per production of biomass it is necessary to multiply 7,633,440 kg of lettuce * 7.37 kg CO_2/kg lettuce = **56,258,452.8 kg of CO_2** or **56,258 tons of CO_2** per year.

CHAPTER 5. CONCLUSIONS, DISCUSSIONS AND RECOMMENDATIONS

5.1 Conclusions

The author believes that just one simple technological solution will not be the answer to an increased and workable food production rather a combination of several methods and strategies are going to lead us to the XXI century green revolution.

(1) Where should a Vertical Farm (VF) be built in an urban or suburban environment within the state of Indiana? For the location of the vertical farm the author has used ArcGIS software and has concluded that the localities more suitable to locate a vertical farm, under the parameters stated, are Anderson, Brazil, Columbia city, Connersville, Gary, Mishawaka, and Terre Haute. To see the specific location of the hypothetical vertical farms see the Appendix A.

(2) What is the relative demand of energy of lettuce production in a vertical farm or controlled environment to provide lettuce for the location 'X'? **133,585,200 kWh** is the total cost of energy of a 100% supplemental lighting vertical farm of 100m x 100m x 10 story, where the 10th building works as a regular greenhouse with natural lighting.

According to the U.S Energy Information Administration in 2012, retrieved from http://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3, the average annual electricity consumption for a U.S. residential utility customer was 10,837 kWh, which means that the estimated consumption of electricity of the vertical farm is equivalent to 12,326 American households of four, which is roughly 50,000 people. This can be also noted to determine the feasibility of 100% of supplemental lighting, when assuming that all the daily needs of fresh edible vegetables are satified with lettuce (see Section 4.4.), the vertical farm would feed slightly more than the 100,000 population. It means that it would be able to feed the population selected in the model used in ArcGIS.

(3) What is the relative demand of water of lettuce production in a vertical farm or controlled environment to provide lettuce for the location 'X'? **The demand of water of the vertical farm of these characteristics will be of 60,304,176 l H_2O/year**, or 60,304.17 ton H_2O/year, or in US units **15,930,677.94 gallons of water/year,** knowing that one-liter is 0.264172 US gallons.

The new water footprint will be 60,304,176 l H_20 per year/ 8,481,600kg lettuce per year = 7.11 l H_20/ kg lettuce, which is over 33 times less water than conventional farming.

According to the United States Environmental Protection Agency, 2011 and its document *US water use – Watersense,* in average, an American household of four will consume 400 gallons of water every day, which is an amount of 146,000 gallons of water per household per year. So the water consumed by the vertical farm can be compared with the amount of water used per household resulting in 109 households of four (437 people).

(4) What is the amount of lettuce produced by the hypothetical vertical farm? **8,481,600 kg or 8,482 ton of lettuce /year produced by the 10 story vertical farm and dimensions of 100mx100m with stacked drums.**

(5) What is the carbon footprint relative to the electric consumption (lighting) of the vertical farm? **56,258,452.8 kg of CO_2** or **56,258 tons of CO_2** per year.

Table 5.1 Comparison between countries of their emissions per capita and the equivalent amount of people that would be needed to produce the same amount of emissions that a Vertical Farm of these characteristics. World Bank table 2009-2013, data available at http://data.worldbank.org/indicator/EN.ATM.CO2E.PC

Country	Ton CO_2/capita (year2010)	Ton CO_2/VF/year	Equivalent People
Spain	5.9	56,258	9,535
United States	17.6	56,258	3,196
India	1.7	56,258	33,092
Canada	14.6	56,258	3,853

(6) Is it feasible to replace mass produced lettuce with locally grown lettuce utilizing vertical farm methods? Under the estimations taken in this thesis, it is feasible to feed more than 100,000 people of any of the populations chosen. The technology to do so exists but under economic considerations it is not clear if it would be feasible. The numbers shown in the energy consumption are very large; to know if it is really feasible to replace mass produced lettuce with vertical farms it is necessary to apply economic factors in the analysis, but it is out of the scope of this study. The author of the present thesis proposes in the Recommendations section (5.3) to include economic factors into consideration for a more precise conclusion and detailed results.

As a final reminder of this section, the author wanted to show again to the reader the delimitations or weaknesses of this research that have lead to these conclusions:

- This research did not focus in the robotization of the food production process.
- The author did not intend to design a new model of vertical farm.
- The research conducted by the author did not analyze all the social implications derived from building a vertical farm.
- The author did not intend to study the feasibility of vertical farming as a method to recover brownfields.
- The author did not study all the crops. This thesis is focused just in leafy greens, specifically lettuce.

- The author did not include in the study the costs of packaging or ventilation.
- The author did not put special emphasis in the distribution chain because it is assumed zero losses in distribution and delivery of the product.
- The author has not analyzed the amount of sunlight and shade positions made by the buildings of the cities in order to find a location suitable for the vertical farm. Some of the criticism to vertical farm located in cities is that the producers will not be able to use natural light or to install solar panels in order to produce electricity because of the shading of the other buildings.
- The research conducted by the author did not analyze in depth how indoor grown lettuce with artificial light affects its nutritional value.
- The relative demand of labor and costs of building construction and land purchasing are out of the scope of this thesis, although the author is going to quickly estimate the land efficiency of the vertical farm production.
- The research of nutrient requirement is out of the scope of this thesis.
- The estimation of carbon footprint is based only in the relative demand of electricity from the artificial lighting.
- The values used are an average for the different varieties of lettuce. This can cause alterations in the real data if calculated for a specific variety of lettuce.
- The comparison between VF and conventional farm is out of the scope.

- One of the assumptions is also a delimitation, considering that the carbon footprint of the 10th floor is zero because does not use supplemental lighting and uses the sun. But the author is not taking in consideration the embodied carbon of the materials, nutrients, or others factors involved.

5.2 Discussions

The author did not consider for the present thesis alternative sources of energy to run the facility, such as, windmills, or photovoltaic (PV panels). For example, PV panels are highly dependent in the availability of hours of sun in certain geographic areas, those with fewer hours of sun due to the proximity to the poles or those areas with tall buildings around, which will compete for the sun on the roofs of the surrounding shorter buildings. An anaerobic digester that could use the wastes from the vertical farm and from the locality would provide energy and would also benefit the locality to reduce wastes, introducing them into the cycle again, as well as reducing the energy consumption of the facility. The author did not focus on the production of energy; instead the thesis focuses on energy consumption; However, for future research the production of energy should be considered, as well as other measures such as mirrors as a source to direct sunlight into a vertical farm greenhouse, systems of ventilation and security for the facility, and architectural concepts to design the facility in order to reduce the energetic losses and increase the input of sunlight are other considerations out of the scope of the thesis.

Similarly, the author did not consider start-up costs or economic and other community benefits of having a local source of employment and fresh produce.

The reason of leaving these considerations out of this research is simply lack of time due to the short period to develop the thesis.

The results of the thesis, although they are thought to be an approximate estimation done with real data from research and professional institutions, have several weaknesses that have driven the author to these conclusions. A major weakness is the use of 760 heads of lettuce/m^2 of production and assigns it to the production of drums. The author had neither the time nor the access to drums for experimentation and to estimate a more accurate number of production. This is something that the author considers to further study in the Recommendations (5.3).

There is much controversy about light spectrum needs of plants. Professor Albright said that the Licor and Apogee PAR sensors have a built-in filter that emphasizes the red and blue ends of the spectrum, and de-emphasizes the wavelengths in between (by about a 30% reduction). This is called the "yield photon flux". They do not "consider all colors of light equally", as the author of this thesis stated. This shape of filtering is based on early work of McKree and confirmed by Anada. Their results suggested relatively more effective photosynthesis at the red and blue ends of the PAR band. However, their work was done at extremely low light intensities and for single leaves - NOT canopies. Thus, the author does not believe there is proof that emphasizing blue and red from LEDs has been proven to be more effective for plant lighting. Red is more energy-efficient on a photon basis, but it is not for sure that blue is more effective for photosynthesis than green, for example. Some blue is needed for morphological reasons, but Professor Albright says that he does not know of proof that a simple 85:15 red/blue spectrum is less desirable for plant growth than other spectra with green/yellow/whatever added.

The author agrees that the conclusions are an approximation of what would show the real consumption of water, electricity and biomass production. However, the numbers shown in the analysis and conclusions are made given the assumptions, limitations and delimitations listed in Chapter one of the present thesis. The author has found that the primary constraint in order to build vertical farms is the electric consumption. This is consistent with the results of the literature review. Note also that the data used to calculate the emissions is data averaged over the entire country.

The actual costs will depend on how reliant the local utility is on coal for electricity and how much of their capacity has been converted to natural gas as the fuel to generate electricity.

Professor Albright, who has been cited several times along this thesis, did not consider either the cost or the savings of water, nor the environmental impacts that conventional farming is doing to the aquifer ecosystem, rivers, lakes, and oceans as well as all the problems involved with erosion, loss of fertile soil and runoff, runoff not of soil but also of pesticides and fertilizers that go downstream, plus the calculation of amount of water used, oil, kWh (units of energy), amount of soil lost, soil used…etc.

To exemplify some of these considerations in a last example, "It is estimated that 2009 plant disease losses, including control costs, amounted to approximately $653.06 million. The value of the crops used in this estimate was approximately $5887.33 million, resulting in an 11.09 total percent disease loss across all crops" Williams-Woodward, Jean L. (2009) p.1. Clearly, avoiding a large portion of these necessary costs of conventional agriculture would be another potential economic advantage for a vertical farm.

The effects on the flavor of the vertically produced vegetables are not given based on actual scientific trials. Consequently, the author considers that there are reasons to be skeptical about this statement "vertical food tastes better", because these commercial vertical farm representatives that advocate for its product are trying to sell it, but with no real scientific evidence.

Locations of customers matter only if they come to the greenhouse to pick up their purchases. But, if they do, this adds to the food miles for total food purchases, unless they are able to walk to the facility. The customers are not going to purchase all their products from the vertical farm. This means that many foods, specially fruits (bananas, apples, cherries…etc.) will likely still be imported, because of their size and weight would make it difficult and challenging to grow trees vertically indoors. Also most of the fruit trees give one crop per year, so it won't matter keeping the controlled environment functioning during the whole year because it would consume too many resources.

It seems more efficient, in that case, for the products that can be grown vertically, to be distributed through the existing marketing channels rather than being sold through separate and parallel marketing centers at the VF itself.

Based on this study about vertical farming, the author has arrived to the conclusion that vertical farming is feasible under ecological and energy considerations, but the economic considerations must still be analyzed. The magnitude of the start-up costs and energy consumed by the hypothetical vertical farm is a major barrier and perhaps the main reason why we are not seeing vertical farms everywhere. Instead of vertical farms, the author has found that there are some commercial facilities within urban areas, such as New York or Chicago, that use supplemental lighting in old, reconfigured warehouses. The author thinks that we are still far from achieving profitable results with the use of 100% supplemental lighting in a vertical farm facility. However, high-tech greenhouses and CEA (controlled environmental agriculture) within the urban and peri-urban environment may be the next step towards a more efficient way to produce food.

The thesis does not compare the price or nutritional value of lettuce grown conventionally versus the price of lettuce grown in the hypothetical vertical farm, so it is unknown how profitable and how long the payback of the initial investment would be, which is huge according to the literature review. Although the purpose of this thesis was not to generate a comparison of vertical farm to conventional open field agriculture, important data that could form the foundation for such comparison were generated. The actual carbon footprint of the conventional farming and the energy in form of fuel embodied are two of the mains factors to consider when comparing it with vertical farming. Both the carbon footprint and the energy needed for food production will depend on the crop, the geography, and how develop is the country where is growing the crop. An example of this variation is stated in figure 5.1 when comparing the equivalent carbon footprint per capita and country, where develop countries have a very different carbon footprint in comparison with countries under developed.

As final critique, Professor Albright says in section 2.4.2 of the present thesis that he doubts we are so short of land that we need to go further, but what the author believes after the development of this thesis is that it is not about if we, in the United States, are short of land. There are places in the world that are short of land, or water, or both, but they have energy, such as Arab countries like Qatar where vertical farming could be a valid answer to food shortage.

On the other hand, as mentioned before, after seeing the magnitude of the numbers, the author of this thesis agrees that the feasibility of the vertical farm as a substitute of mass produced lettuce is doubtful, at least with the current state of art of technology, and that in fact, now is better to invest and to innovate in greenhouses with aeroponic/hydroponic system.

In conclusion, the author wants to remind that the results shown can be affected and in fact are affected by the assumptions, the limitations, and the delimitations, see chapter 1, section 1.6, 1.7, and 1.8 respectively.

5.3 Recommendations

In this last section of the thesis, the author wanted to include areas of interest for further research and future investigation.

1. For further research it is necessary to calculate the energy required for the environmental control (as dehumidifiers, ventilation, etc.) and for monitoring and services of the vertical farm.
2. The economic cost of installation of these environmental control devices and costs of implementation for monitoring & services. As well as the economic costs of building construction and land purchasing should be studied.
3. For further research the author recommends to focus on the feasibility of implementing passive initiatives to reduce energy and water consumption, such as a passive house design for the model.
4. Professor Louis Albright makes the next question, what is the carbon footprint associated with obtaining sufficient light to grow a food crop with 100% supplemental light? The author of the present study has developed an estimation in the amount of CO_2 generated that can give a first impression of carbon footprint and impact on the environment from the vertical farm. It is obvious that all human activity has its impact on the environment; even the idea of vertical farm has its negative face.

   A comparison of methods would be an interesting topic for further research. How is the actual footprint of the conventional farming? And is that way of producing food sustainable or not?

5. As mentioned before, in the thesis there are several loses in both the seedling process and the distribution chain in conventional farming, also long distance shipping ages the product, lowering quality when it finally reaches the customer – leading to more customer discard and waste. The author considers that it would be necessary for more accurate comparison between conventional and vertical farming to study the differences in those processes.
6. A cost-benefit analysis of the vertical farm systems compared with a cost-benefit analysis of conventional farming would be the best way to analyze the economical feasibility of the vertical farm methods.
7. The author recommends to closely following the Japanese experience because Doctor Takakura, through Doctor Albright, has commented that after the governmental subsidies end, they will go out of business. This information reveals that the plant factories (Japanese vertical farms) do not cover their costs and are not economically feasible. This experience should be used to examine closely similar experiences in the United States as well as other countries with similar project, in order to determine with real evidence if vertical farms are economically feasible.
8. After the developing of this thesis, the author has learned that the most important aspect of research is to formulate the right questions.

   In order to provide guidance for future research, the author of the present thesis suggests the following questions to be answered:

   (1) Do vertical farms have an advantage over local CEA greenhouses?;

(2) Is it feasible to replace mass produced (X product) outdoors, in contrast to production in local greenhouses?.

9. The estimation of 760 heads of lettuce production per square meter taken from Cornell University applies only with the raft system where the plants can be re-spaced in two directions. In the words of Professor Albright, this comes back to the question of how a structure can hold the weight of the ponds, if they were used. It also raises the question whether or not plants can be re-spaced in the drums. A very useful study would be to estimate the real productivity of the drums through experimentation, so the numbers of production of lettuce per unit or area are more precise.
10. Consider in future research the cost of decontamination of the Brownfields, if these were contaminated, in order to increase the willingness of the people to become customers of products grown there. Also, to study the feasibility of vertical farming as a method to recover brownfields.
11. Consider CO_2 supplementation to save perhaps a third of the lighting. The author did not list CO_2 as an input, suggesting it will not be supplemented. It means that CO_2 will be needed for the crop unless there is sufficient ventilation using outside air. The other option is to use air conditioning to block the need for venting. If this is the case, and there is little air leakage, the CO_2 concentration can be raised (e.g., to 1500 pp for example) to make the artificial lighting more efficient. According to

Professor Albright in Cornell University they have data to suggest the lighting can be reduced by approximately one-third if this is done in a closed facility.

12. Based in the information provided by Professor Albright the author considers that it is needed more research to determine what spectrum is more or less desirable for plant growth than other spectra.

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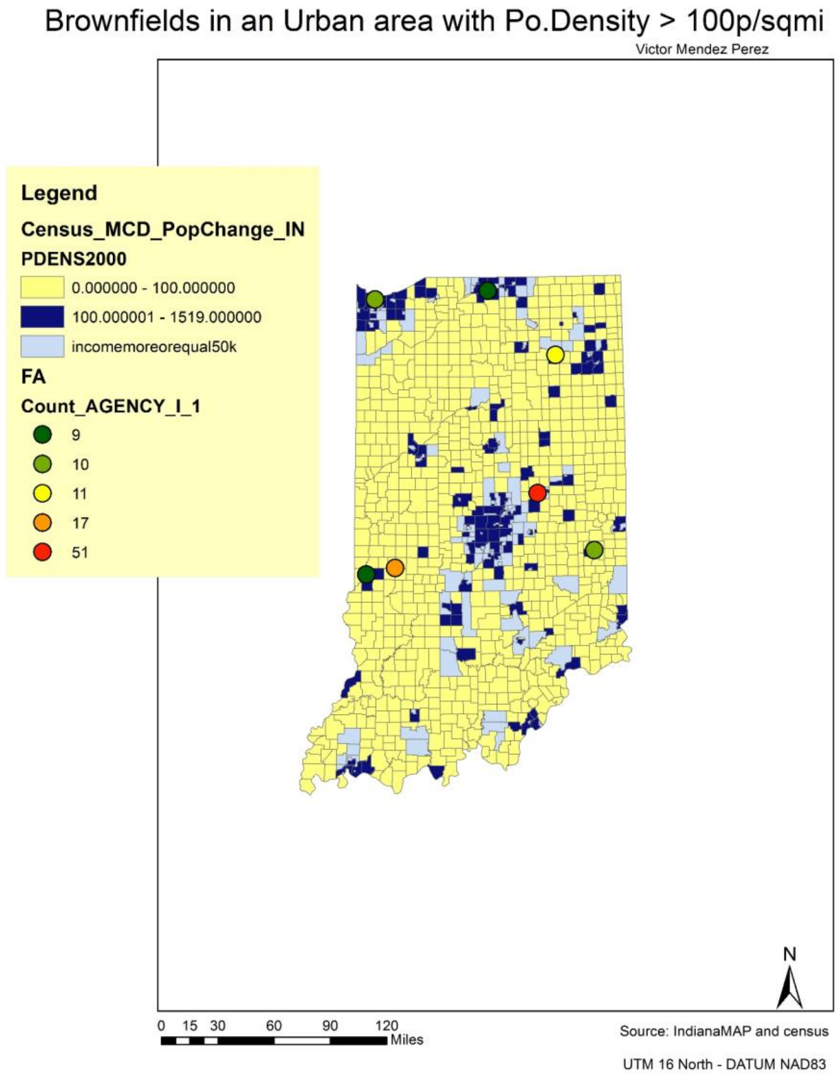
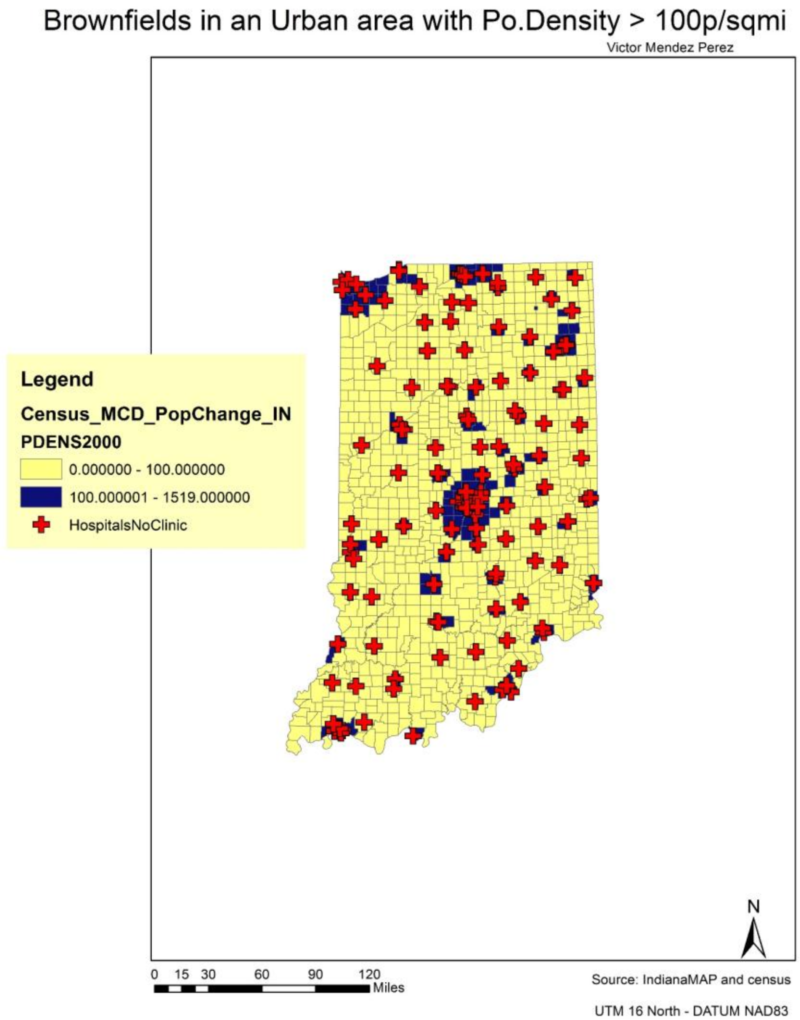
APPENDICES

Appendix A: map of suitable location for a vertical farms in the State of Indiana.

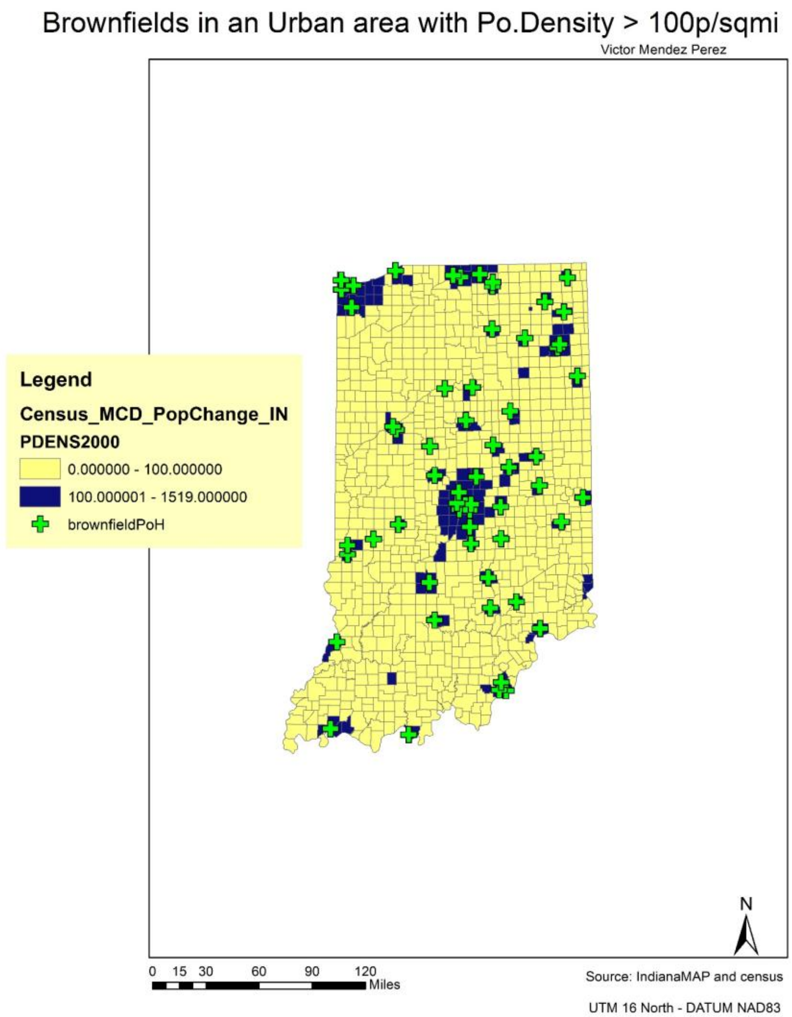


The localities more suitable to locate a vertical farm, under the parameters stated, are (from left to right and from up to down) Gary, Mishawaka, Columbia city, Terre Haute, Brazil, Anderson and Connersville.

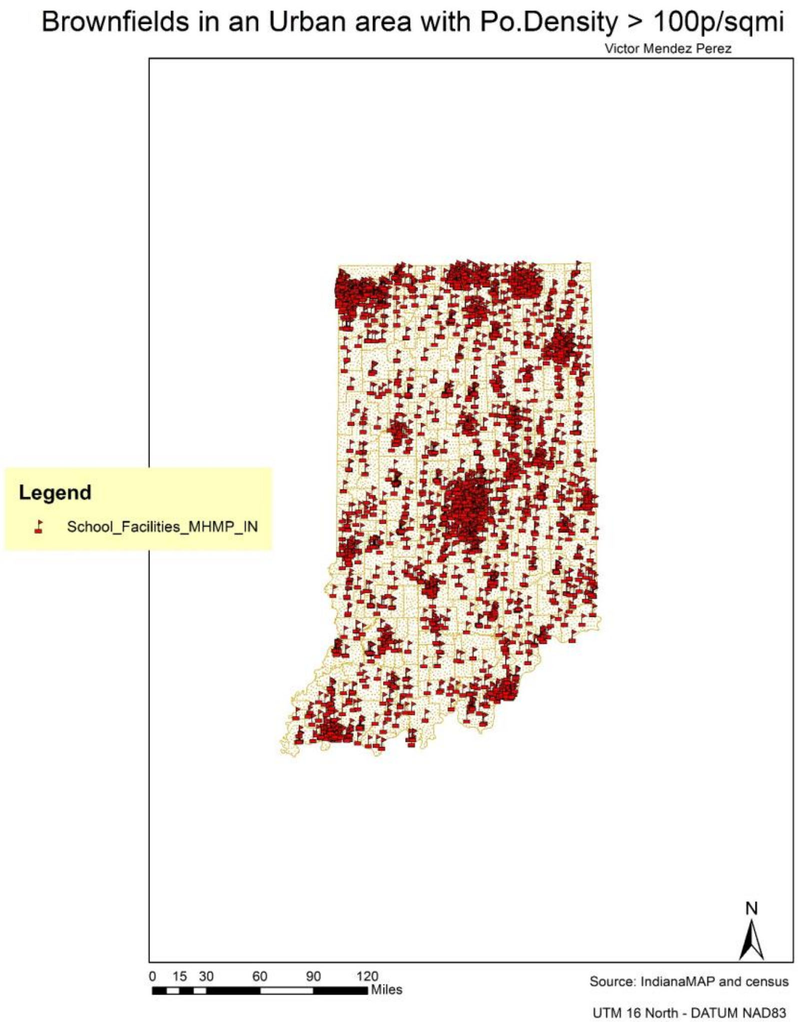
Appendix B: map of the location Hospitals but not clinics within areas of population with more than 100 people per square mile in the State of Indiana.



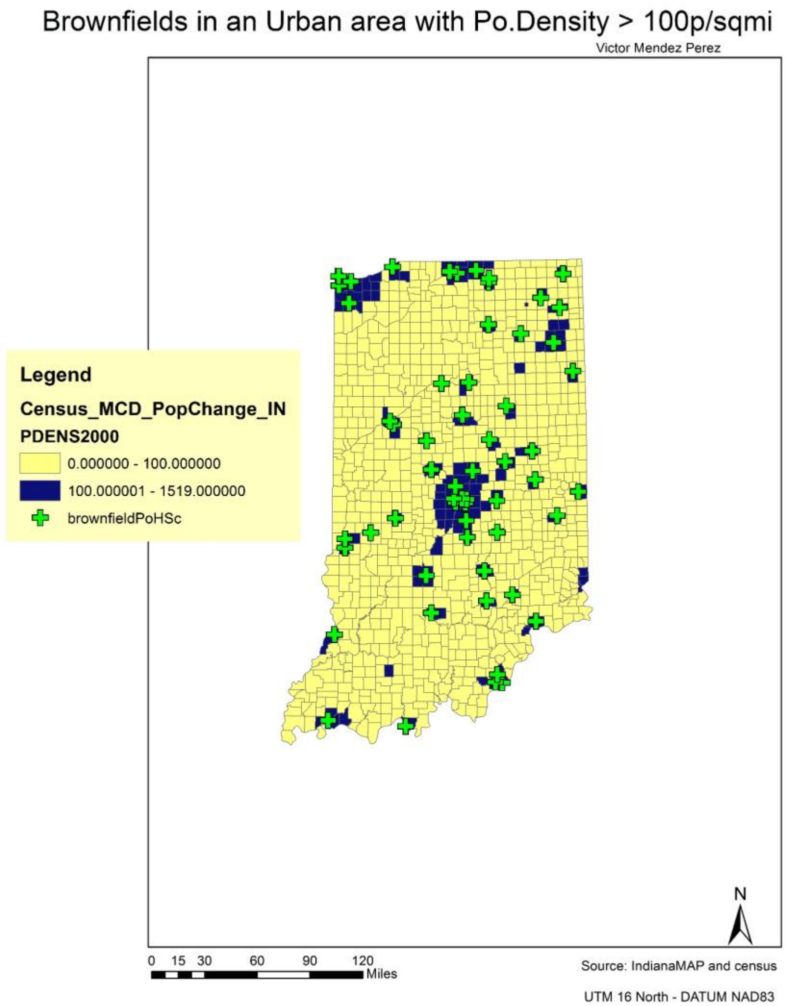
Appendix C: map of the location of Brownfields in a radius of two kilometers of Hospitals but not clinics and within areas of population with more than 100 people per square mile in the State of Indiana.



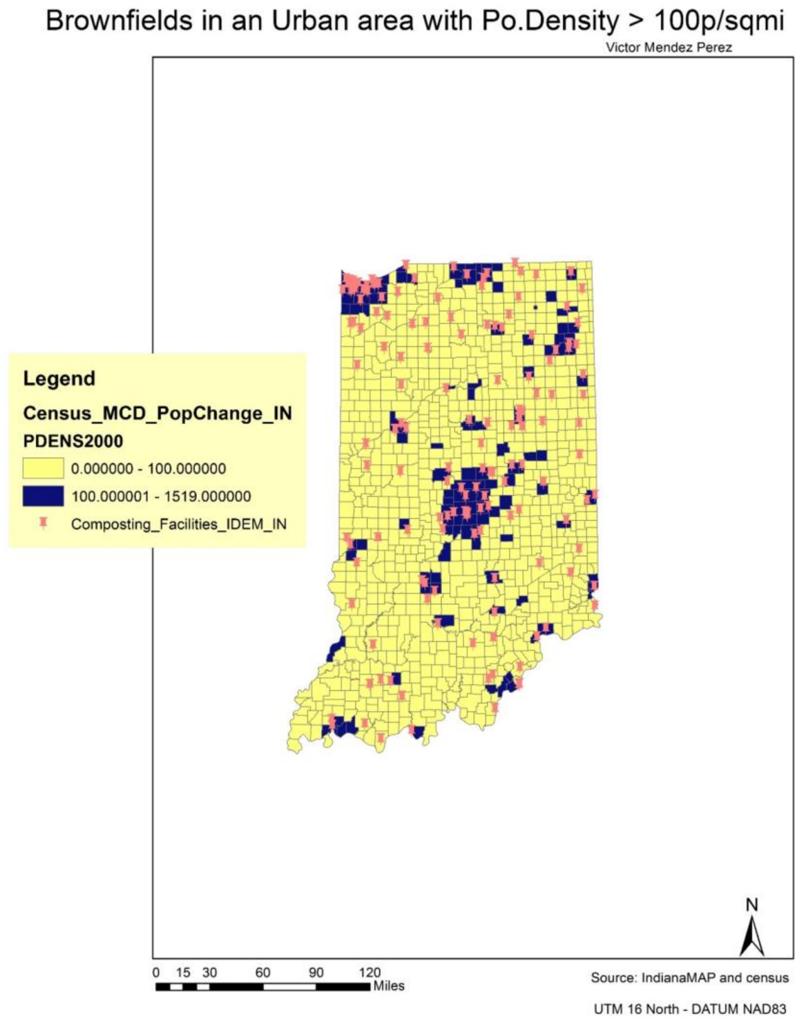
Appendix D: map of the location of all the schools in the State of Indiana.



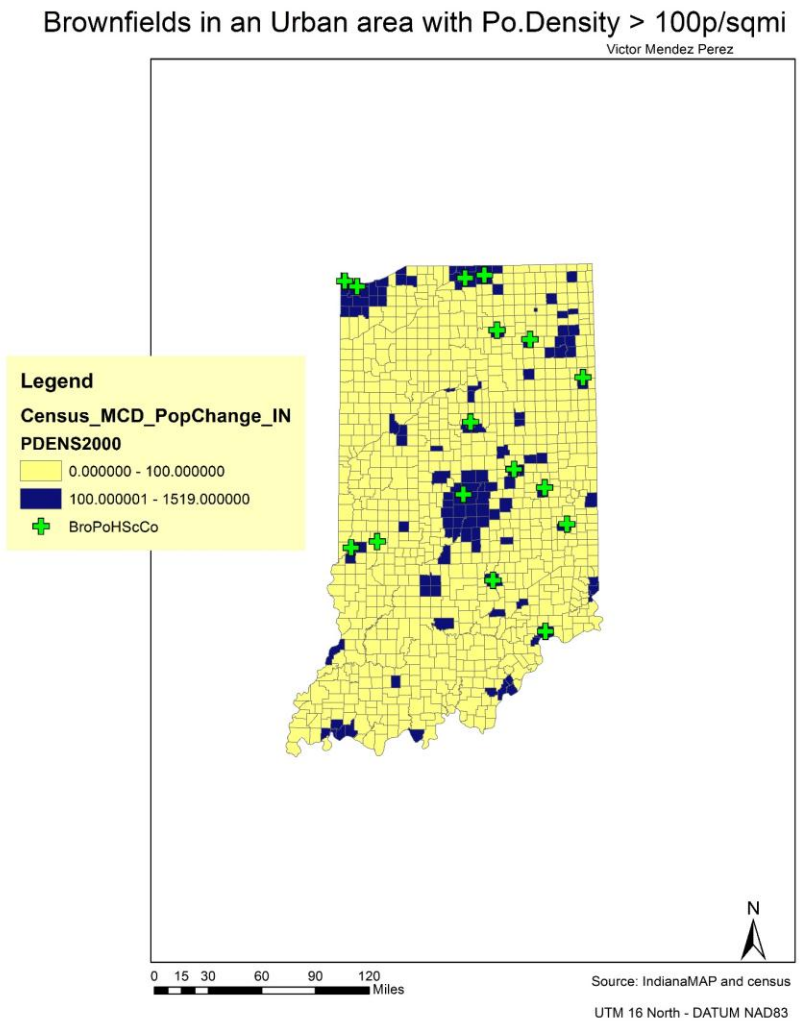
Appendix E: map of the location of Brownfields in a radius of two kilometers of Hospitals but not clinics and schools, within areas of population with more than 100 people per square mile in the State of Indiana.



Appendix F: map of the location of composting facilities within areas of population with more than 100 people per square mile in the State of Indiana.



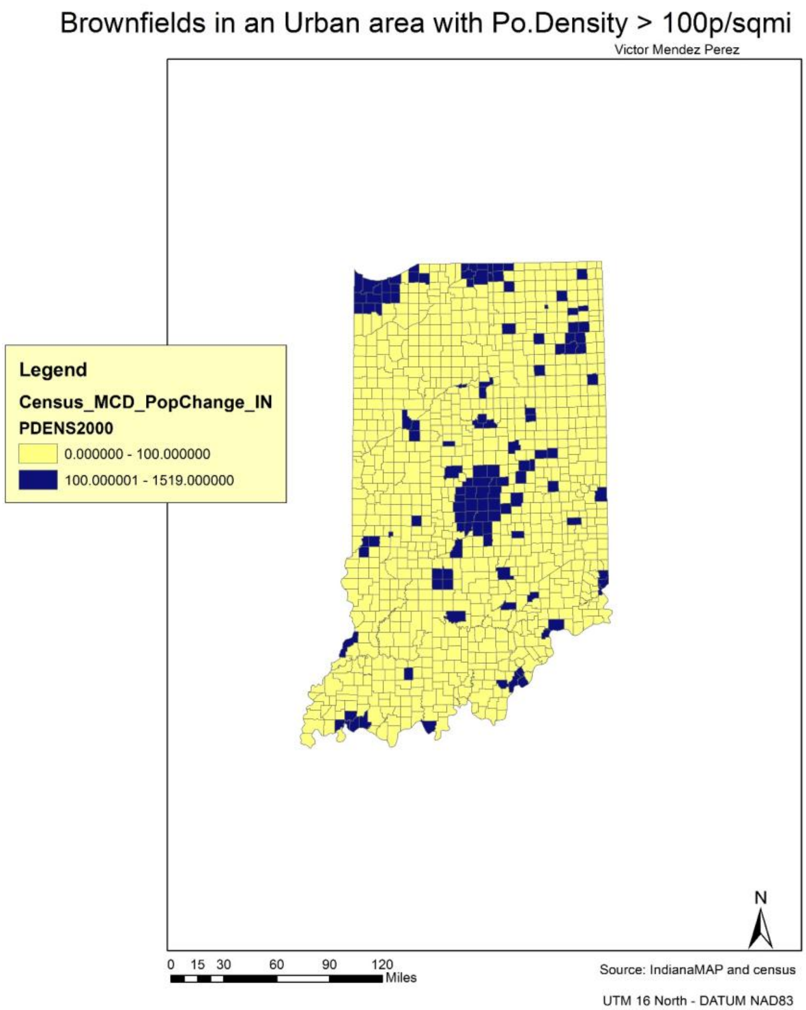
Appendix G: map of the location of Brownfields in a radius of two kilometers of Hospitals but not clinics, schools, and composting facilities, within areas of population with more than 100 people per square mile in the State of Indiana.



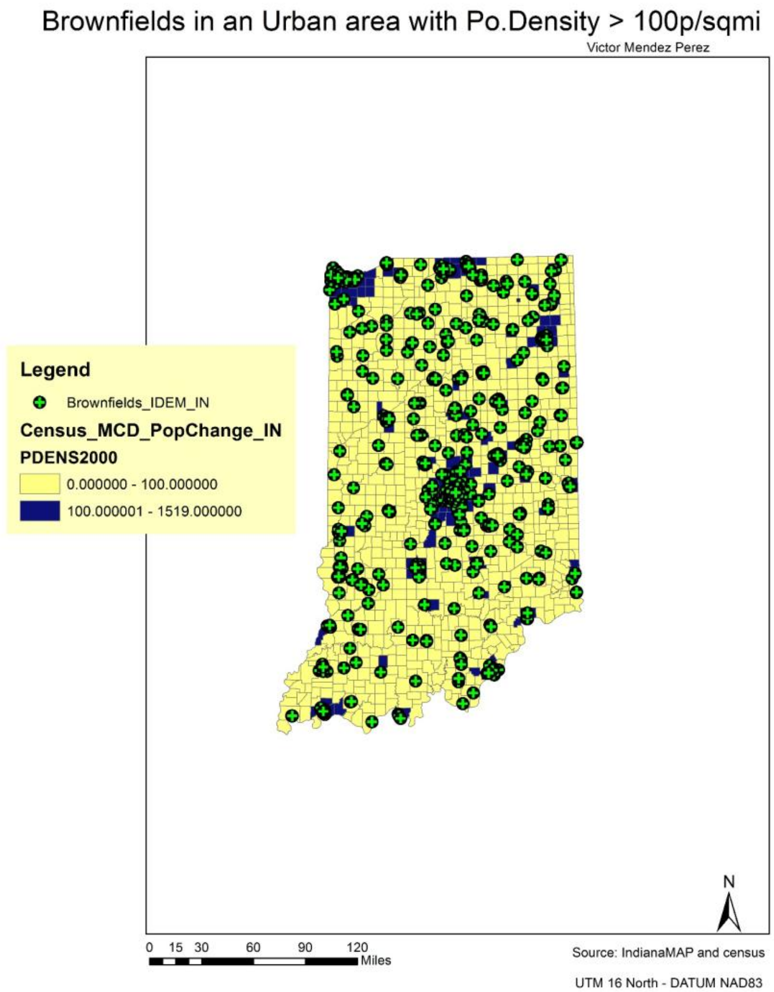
The following three maps show the initial stages of the present study. The first map (Appendix G) is the selection of the population of interest.

The second (Appendix H) is the map with the Population (Po) and all the Brownfields of Indiana, and the third map (Appendix I) displays the brownfield that are only in the area of interest (dark blue).

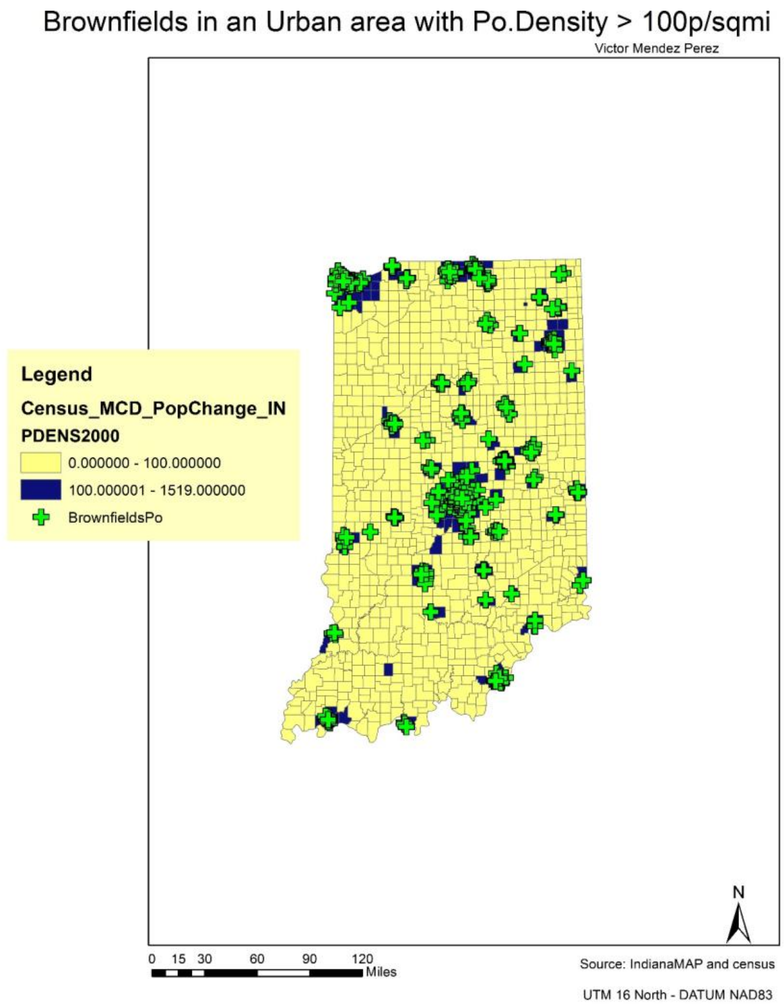
Appendix H: map of the location of the areas of population with more than 100 people per square mile in the State of Indiana.



Appendix I: map of the location of all the Brownfields and the areas of population with more than 100 people per square mile in the State of Indiana.



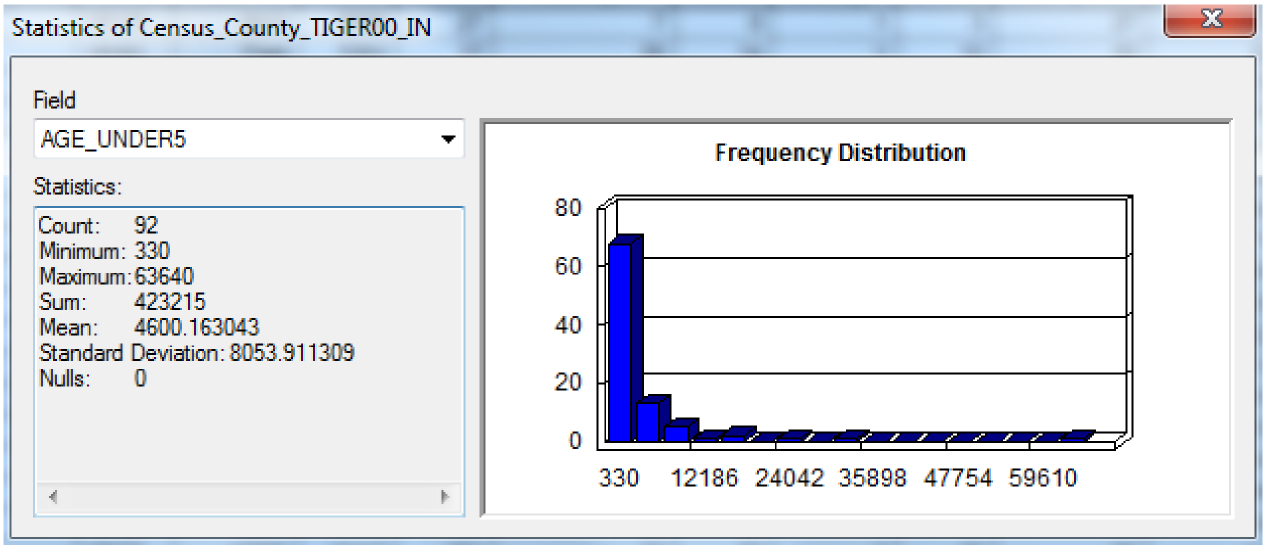
Appendix J: map of the location of only the Brownfields within the areas of population with more than 100 people per square mile in the State of Indiana.



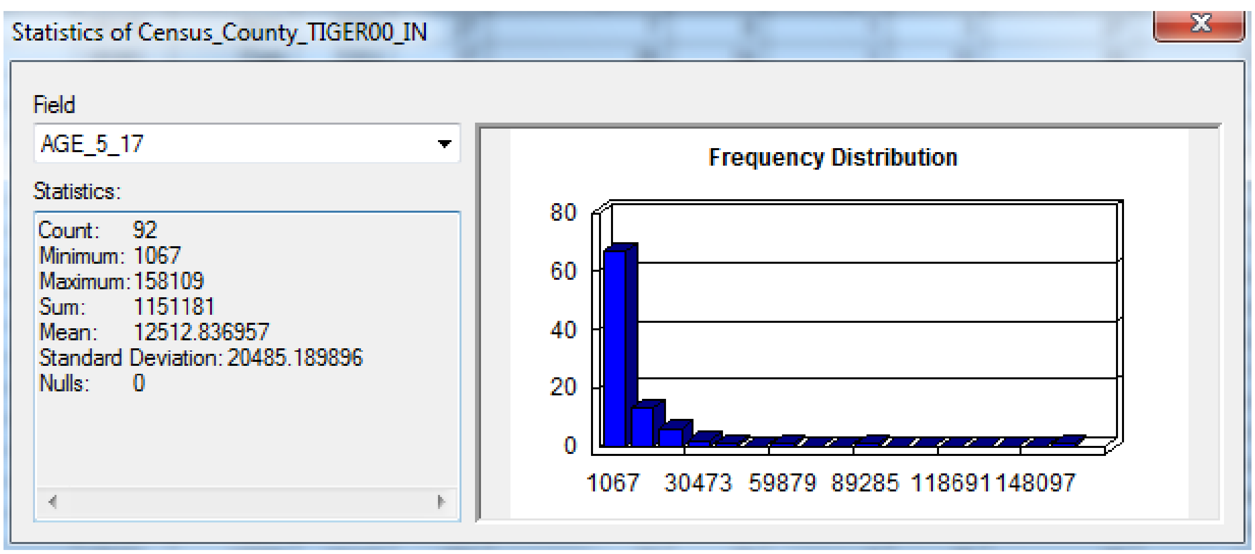
The following appendices are the statistical data used to constrain the location of the vertical farm.

Locate young population, considered by the author of the present study of age under 39.

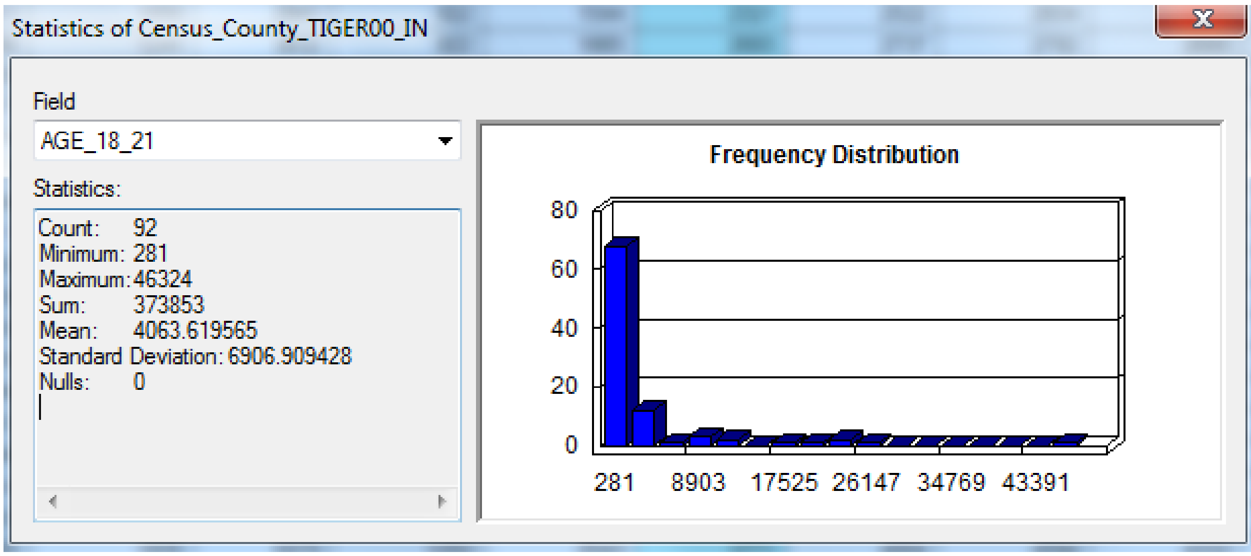
Appendix K: Statistics of population of age under five. From K to the T appendices, the x/axis shows the total of people of that group of age and the y/axis the percentage of counties with that population.



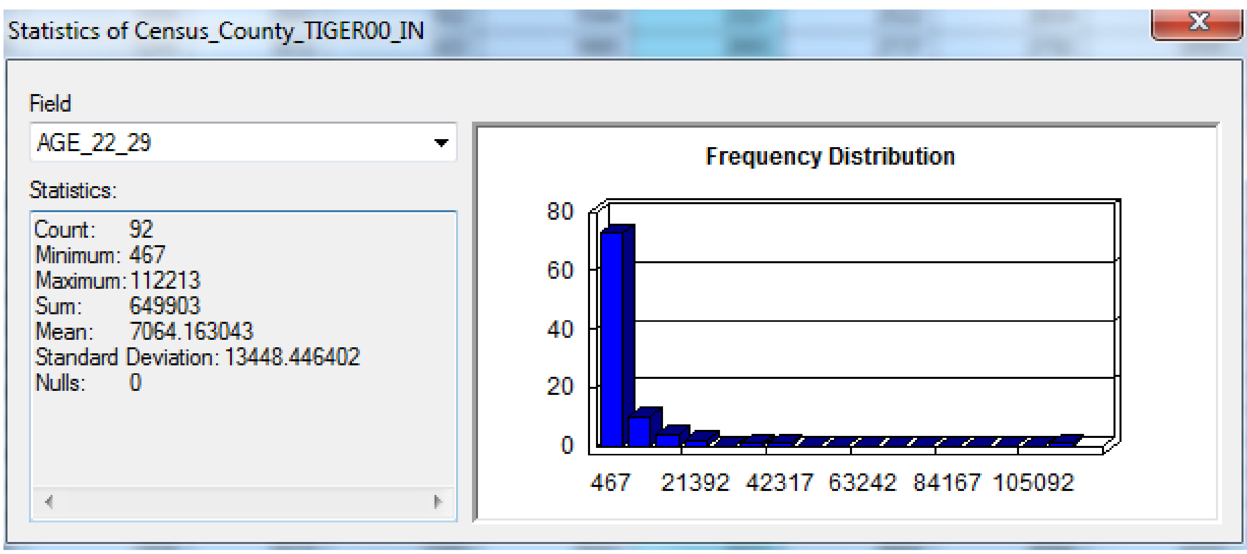
Appendix L: Statistics of population of age between five and seventeen.



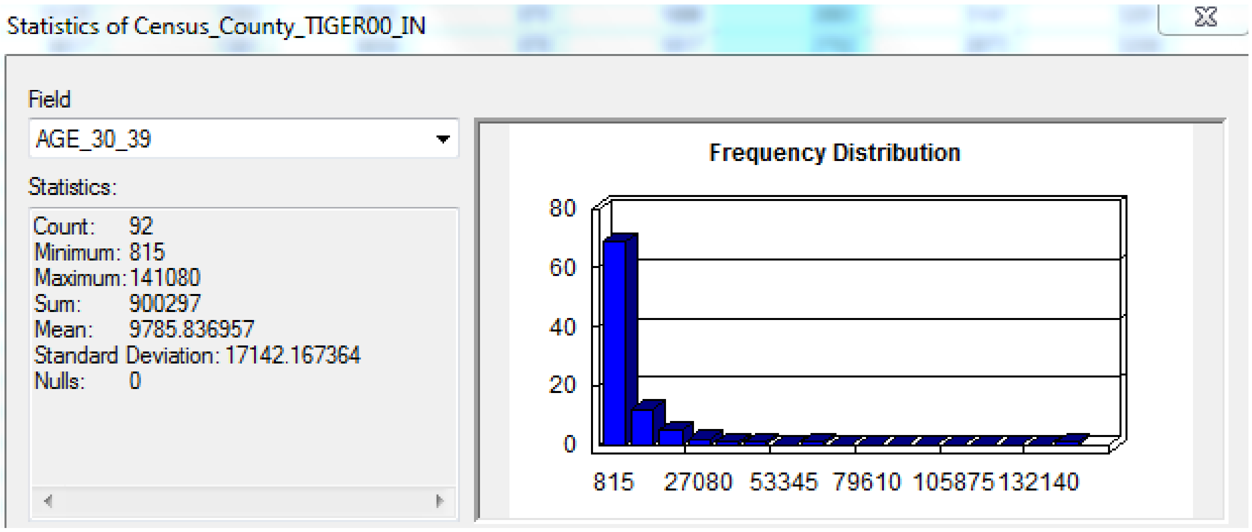
Appendix M: Statistics of population of age between eighteen and twenty-one.



Appendix N: Statistics of population of age between twenty-two and twenty-nine.



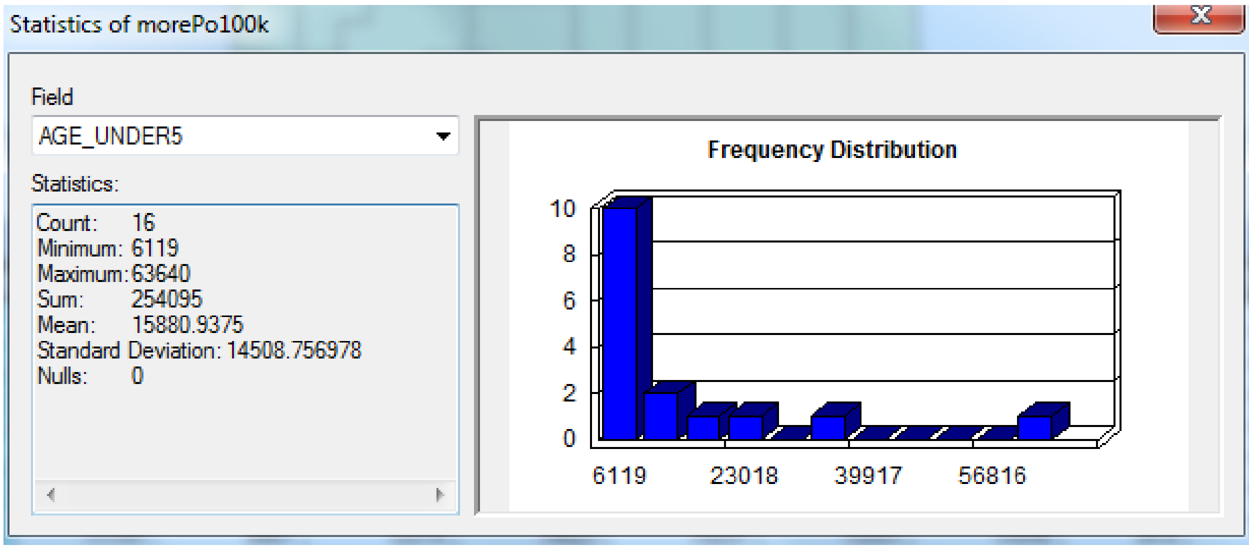
Appendix O: Statistics of population of age between thirty and thirty-nine.



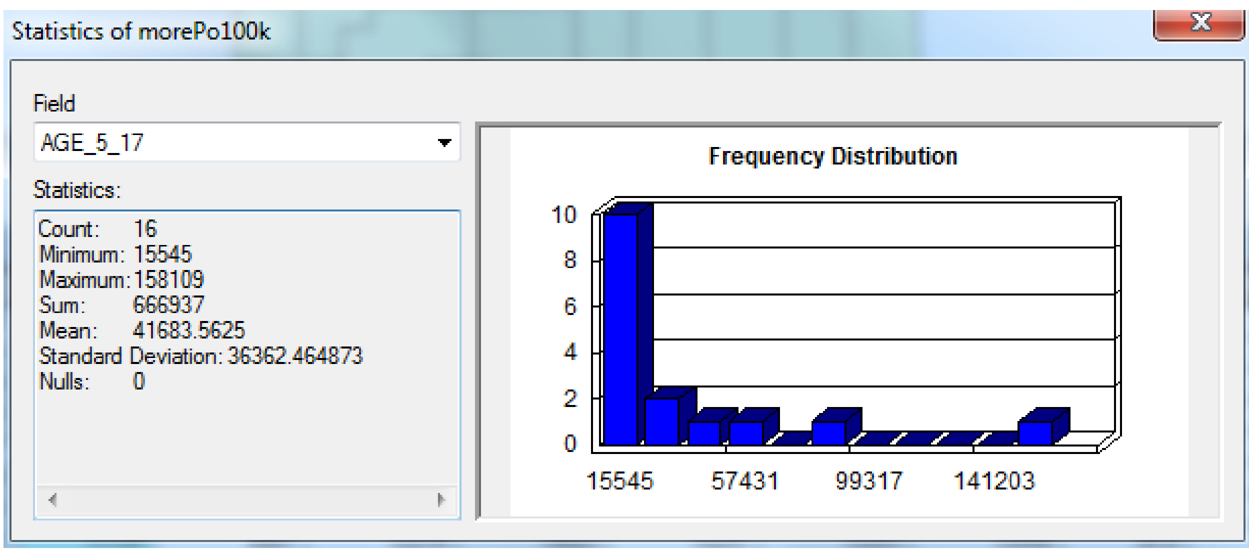
The author has selected the groups of age of interest from the layer 'morePo100k', which is the layer that represents areas with population greater than 100.000 people.

From O to the S appendices, the x/axis shows the total of people of that group of age and the y/axis the number of counties with that population.

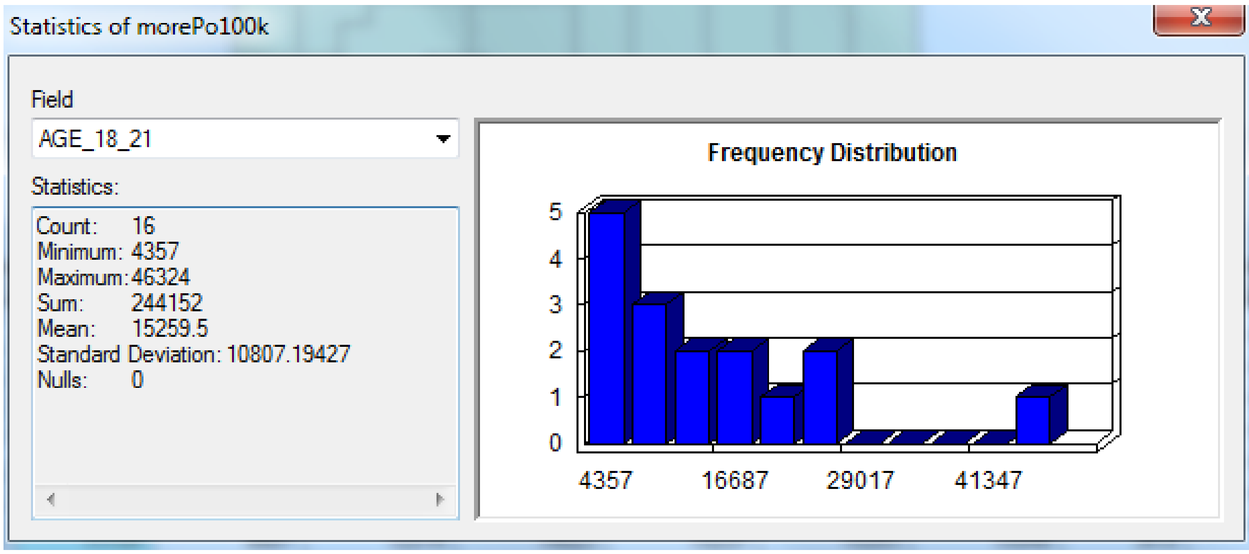
Appendix P: Statistics of population of age under five within areas of population of more than 100,000 people.



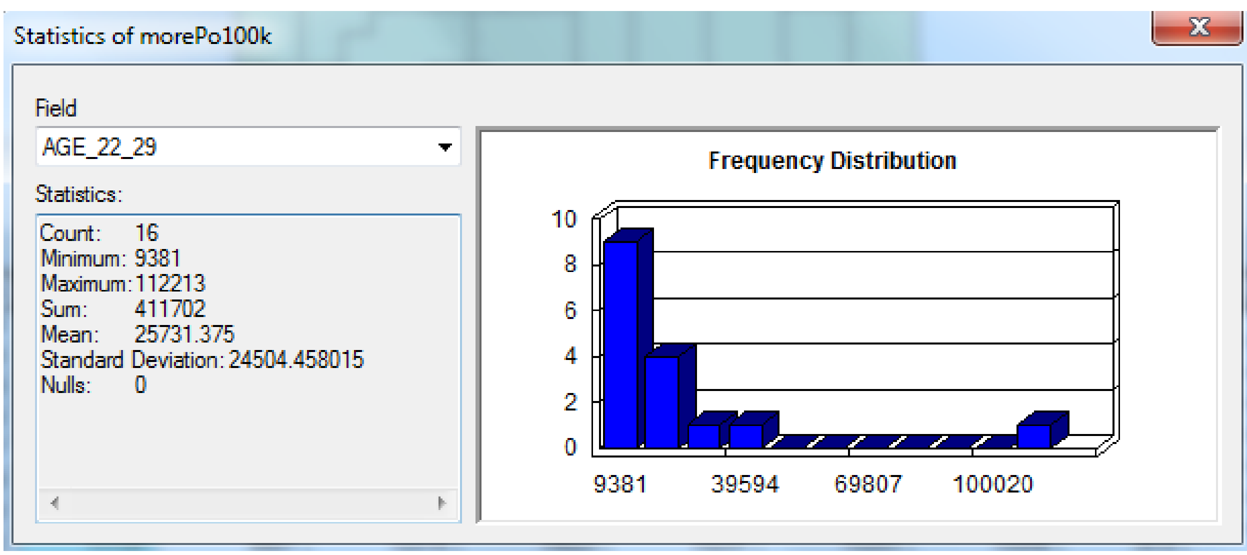
Appendix Q: Statistics of population of age between five and seventeen within areas of population of more than 100,000 people.



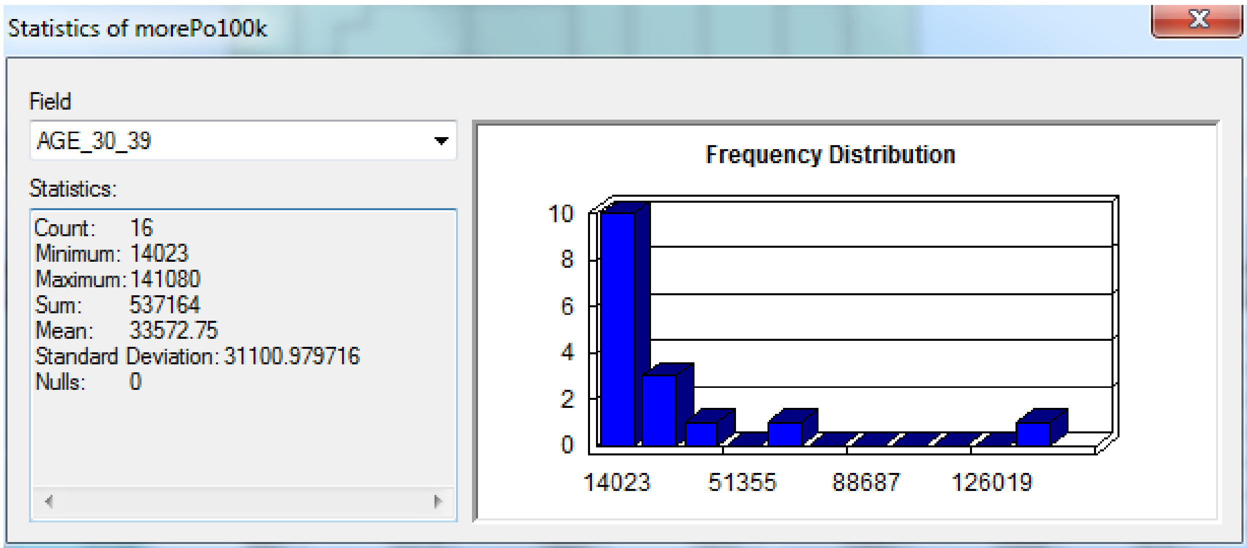
Appendix R: Statistics of population of age between eighteen and twenty-one within areas of population of more than 100,000 people.



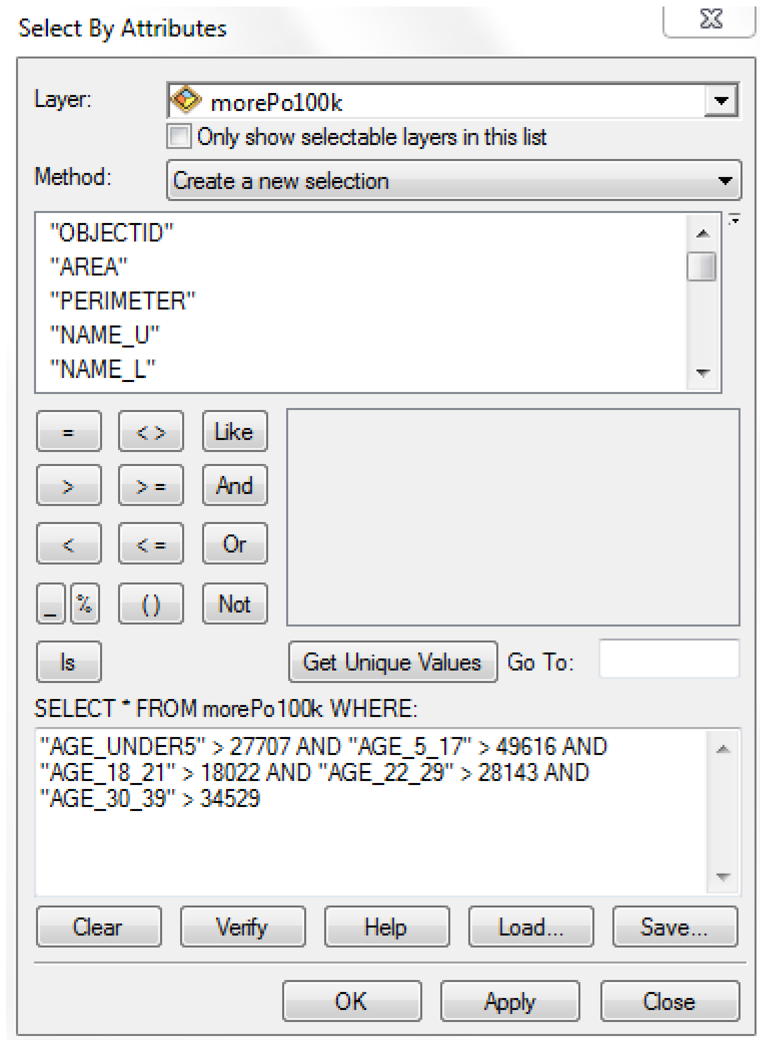
Appendix S: Statistics of population of age between twenty-two and twenty-nine within areas of population of more than 100,000 people.



Appendix T: Statistics of population of age between thirty and thirty-nine within areas of population of more than 100,000 people.

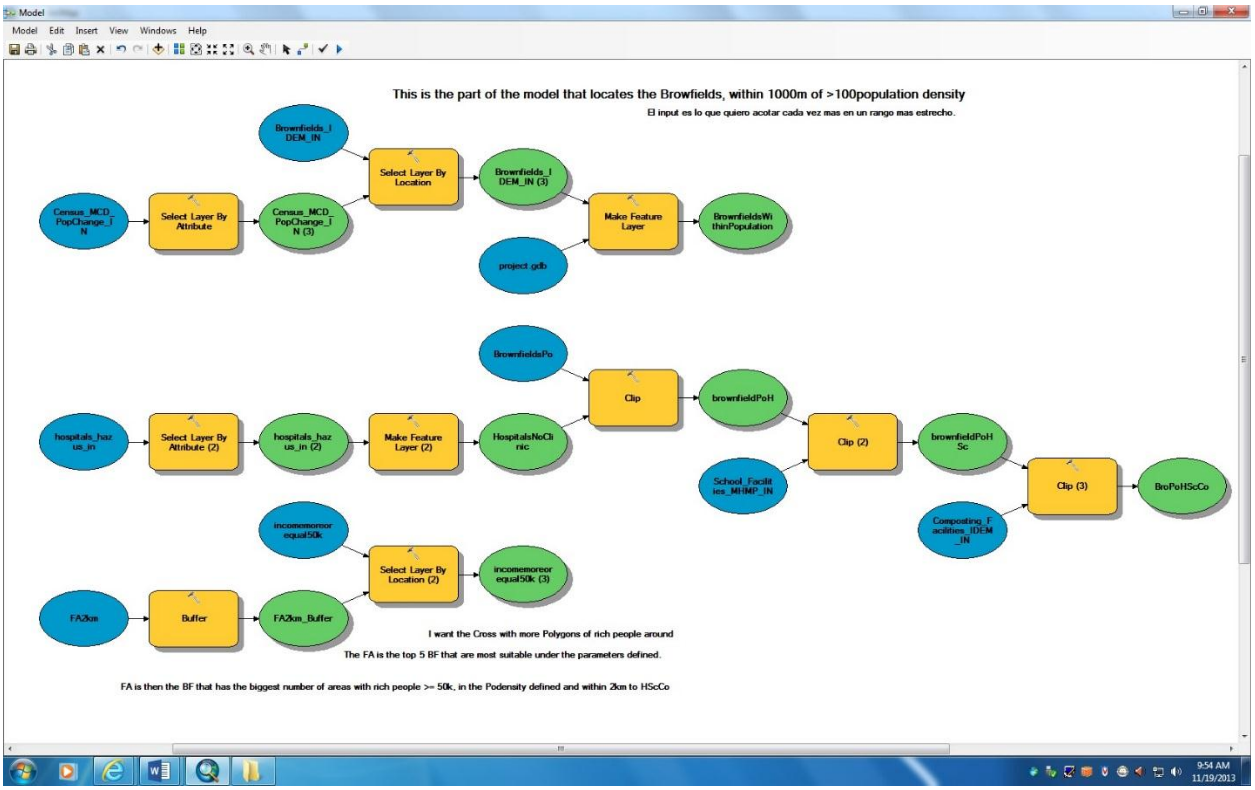


Appendix U: Selection by attributes of the groups of age of interest, with statistical considerations (slightly greater than the mean to reduce areas) within the areas of population greater than 100,000 people.

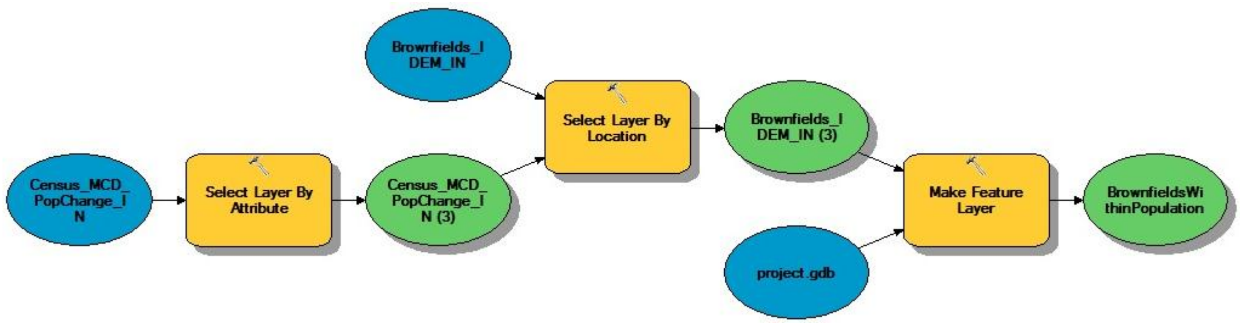


Selecting from under5 (babies and little kids) to young population (in age of having kids) = until 39. After seeing the numbers and statistics the author chose those values because are the higher ones and doing so it can defined more precisely a location of the hypothetical vertical farm.

Appendix V: Built GIS model to locate the most optimal location for the vertical farm.



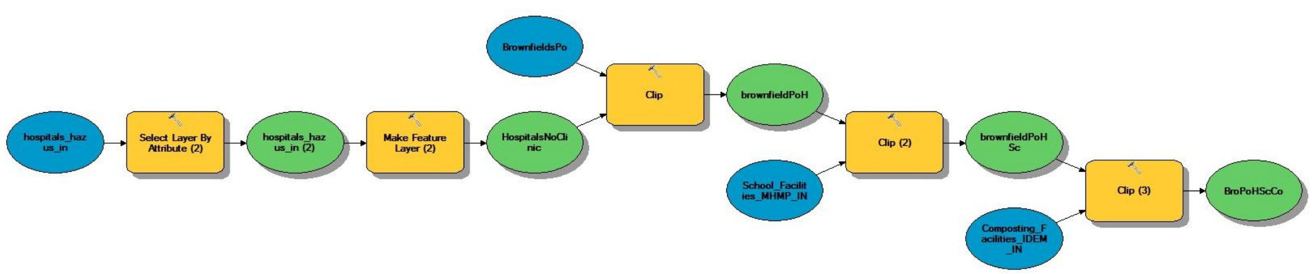
Appendix W: First part of the model.



Select the population by attribute as we have seen in the images in the page before.

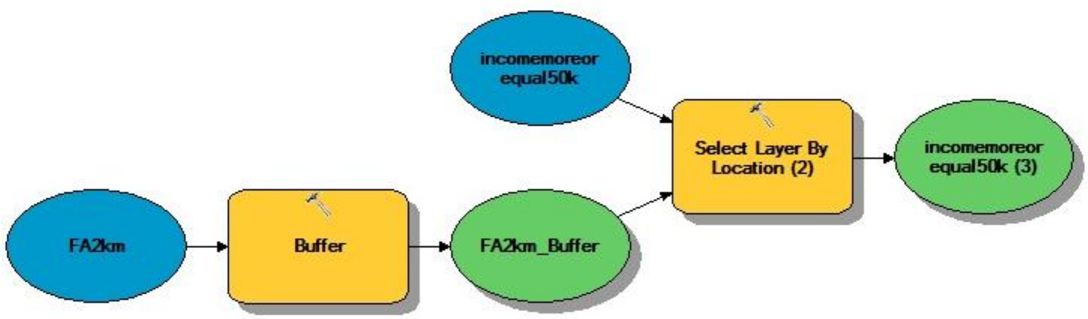
With a Population of more than 100.000 people and being young with children the majority the author selected the Brownfields within this areas.

Appendix X: Second part of the model.



After downloading the layers necessary to continue with the model. The author selected only the hospitals from the Hospitals/Clinics layer, and created a new layer with this data. Then, with the layer created in the 1st part of the model the author used the tool Clip with the Brownfield within the areas of Population selected and also WITH Hospitals that serve food (distance→ within 2km). The same tool "Clip" is used in the new layer created in the very anterior step to locate Brownfields within 2km to a School (to provide organic and healthy food to the kids) , and also within 2km to a Composting Facility (to provide of biomass from the non-edible parts of the crops).

Appendix Y: Third part of the model.



After reducing the number of Brownfields from the initial 789 to 32 (FA2km). The author created a buffer for all the remaining points of interest (brownfields) of 10km of radius to select the ones that have the most points/areas around them with population with income equal or greater to 50.000$.

Appendix Z: Letters to panel of experts (Louis Albright, Natalie Carroll, Cary Mitchell, Vincent Bralts)

Hello prof. Albright,

My name is Victor; I am an international grad student from Spain finishing my thesis at Purdue University.

The theme of my thesis is a proof of concept of the vertical farm, in terms of energy and water when producing lettuce, in a peri-urban area within the state of Indiana.

As I advanced in the development of my thesis I have been working with prof. Mitchell and prof. Bralts, both helped me with very useful inputs. This last visit with Doctor Bralts, encouraged me to try to contact you since I am using for the analysis data from Cornell University that was specifically from you.

So, the reason I am writing to you is to ask if you could check/review the analysis of my thesis and tell me if it looks correct, makes sense…¦ and is good to go. As part of my analysis I considered to have some feedback from a panel of experts, and I thought of you. If you do not have the time to do so, I understand, but in that case I would appreciate it if any of your graduate/PhD students or teacher assistants, or any professor or person with knowledge of the industry that you may know could do me this favor.

I am attaching just the analysis chapter, but if you need to see the rest tell me.

I have some doubts about the estimations of energy consumption that I have done.

I wrote in the thesis that those numbers are worst case scenario and very conservative estimations.

Thank you very much for your time and any help.

Appreciatively,

Víctor

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Hello prof. Carroll,

As we were talking in person and via email I added to my thesis of the vertical farm data relevant from studies made by prof. Albright from Cornell University. The reason I am rewriting to you is to ask you if you could check/review the analysis of my thesis and tell me if looks correct, makes sense… and is good to go. As part of my analysis I considered to have some feedback from a panel of experts, and I thought in you for that. If you do not have the time to do so, I understand, but in that case I would appreciate if any of your grade students or teacher assistants, or any (professor or person from industry) that you may know that could do me that favor.

I already talked to my prof. Dyrenfurth and he said that is fine if people from my committee are also part of my panel of experts.

I am attaching just the analysis chapter, but if you need to see the rest tell me.
I have some doubts about the estimations of energy consumption that I have done. I based my calculations in data from Cornell University.

I wrote in the thesis that those numbers are worst case scenario and very conservative estimations.
Said that, I wanted to thank you for the inputs in the time that we met, and also by email. It has been a real difference in quality of information after talking to you.
Can I meet you in your office at any hour during next week (or whenever you have already taken a look to the analysis)? I am available all the mornings, and afternoons, except Tuesday and Thursday afternoons.

Thank you very much for your time and help,

Víctor

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Hello prof.Mitchell,

This is Victor, from Spain, we talked in person in your office and via email also. I hope everything is going well was good to rest.

As we were talking in person and via email I added to my thesis of the vertical farm data relevant from studies made by prof. Albright from Cornell University. The reason I am rewriting to you is to ask you if you could check/review the analysis of my thesis and tell me if looks correct, makes sense… and is good to go. As part of my analysis I considered to have some feedback from a panel of experts, and I thought in you for that. If you do not have the time to do so, I understand, but in that case I would appreciate if any of your grade students or teacher assistants, or any (professor or person from industry) that you may know that could do me that favor.
I am attaching just the analysis chapter, but if you need to see the rest tell me.
I have some doubts about the estimations of energy consumption that I have done.
I based my calculations in data from Cornell University, specifically from prof. Albright.
I wrote in the thesis that those numbers are worst case scenario and very conservative estimations.

Said that, I wanted to thank you for the inputs in the time that we met, and also by email. It has been a real difference in quality of information after talking to you.

Can I meet you in your office at any hour during next week (or when you have taken a look to the analysis)? I am available all the mornings, and afternoons, except Tuesday and Thursday afternoons.

Thank you very much for your time and help,

Víctor

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Hello prof. Bralts,

I hope the weekend was good to rest. I am feeling well, I will see you in class on Wednesday hopefully.

I was writing to you as we talk in class a couple weeks ago. If you could check/review the analysis of my thesis and tell me if looks corrects, makes sense… and is good to go.

I am attaching just the analysis chapter, but if you need to see the rest tell me.

I have some doubts about the estimations of energy consumption that I have done. I based my calculations in data from Cornell University, specifically from prof. Albright.

I wrote in the thesis that those numbers are worst case scenario and very conservative estimations.

Said that, I wanted to comment to you also this. I have other numbers from other source (a dissertation from Waterloo University, in Canada), that gives me numbers very different, much more optimistic in both productivity (amount and weight of the lettuce) and also in less electrical consumption.

The thing is that I have been comparing these two estimations and see what numbers give each one. My questions are, what would you do? I mean, should I let it as it is and in the chapter 5 of the thesis say that in the DISCUSSION section?

Can I meet you in your office at any hour during this week (or when you have taken a look to the analysis)? I am available all the mornings and afternoons except Tuesday and Thursday.

Thank you,

Víctor