ADVANCED FOOD TECHNOLOGIES

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Introduction

Modern industrial agriculture has increased food production to remarkable levels, sustaining record populations, reducing income spent on food, and even generating non-consumptive purposes for crops, such as harvesting corn for ethanol production. However, the limited supply of arable land, the increasing pressure of urbanization, the shifting growing conditions resulting from climate change, and the negative impacts of industrial agriculture have spurred research into developing technology that divorces food production from traditional agricultural areas – including developing methods of growing food in urban environments.

Urban agriculture comes with its own host of obstacles. Urban soil has frequently been contaminated through industrial processes. Poor air quality compromises the safety of consuming urban-grown plants. Limited and disjointed space means economies of scale cannot be achieved in production as is seen in industrial agriculture. Advanced food technologies have been developed attempting to overcome these urban limitations. These represent scientific advancements which enable humans to grow food in environments that have never been cultivated before and also represent changing cultural perspectives where agricultural is increasingly perceived as a scientific process, not bound to land or natural systems.

A Brief History of Food Technology

In 1840, an important discovery initiated the "scientification" of agriculture. Baron Justus von Liebig identified nitrogen, phosphorus, and potassium (NPK) as the three elements necessary for plant growth. Agriculturalists began to believe that these three elements alone were responsible for soil fertility, ignoring other soil inputs and systems, and farming began to engage in mechanized (as opposed to natural) systems of production (Pollan 2006). Chemical fertilizer, based on supplying NPK, was the first major technological development in industrial agriculture.

Artificial fertilizers came to prominence in the U.S. after World War II. With a surplus of ammonium nitrate remaining from explosives manufacturing, the U.S. government sought potential uses. It was decided it should be used in the production of fertilizer. The new chemical fertilizers were deployed across American agricultural lands, dramatically increasing crop yields (Pollan 2006).

Another major technological innovation in agricultural production includes the use of genetically modified crops. Commercially deployed in 1996 (International Service for the Acquisition of Agri-Biotech Applications 2011), seed crops have been genetically altered to require less water, react optimally to tailored fertilizers, and be resistant to herbicides.

Food technology research has always focused on overcoming the limiting factors of agriculture. Early food technologies such as chemical fertilizers, herbicides, and pesticides overcame limitations of soil quality, competing species, and pests. Contemporary urban agriculture research seeks to develop food technologies which overcome the limitation of plant growth being bound to natural systems – these technologies divorce plant growth from soil, sunlight, open-air climates, growing seasons, and the need for vast swaths of agricultural land.

Figure 1 - Hydroponic strawberries. Source: The Innovation Diaries.

Urban Agriculture: Open-Environment/Controlled-Environment

There are two broad categories of urban agriculture: 1) open-environment agriculture which leaves plants exposed to unmitigated air, weather, and sunlight (e.g., community gardens and rooftop farms); and 2) controlled-environment agriculture (CEA) where air quality, temperature, and lighting are highly regulated (e.g., greenhouses and vertical farms).

Open-environment farming in an urban context has many limitations. Former industrial processes have sometimes contaminated the soil and vehicle exhaust reduces air quality. Furthermore, dense urban areas often lack enough open land to enable economically viable farming.

Controlled-environment agriculture provides an alternative growing space which overcomes the problems associated with open-environment urban farming. These constructed environments protect indoor plants from contaminated air, control temperature and humidity, utilize artificial lighting, do not require pesticides, enable the highly efficient use of water and fertilizers, and circumvent open space limitations by building vertically.

Plants cultivated in controlled environments are almost completely removed from natural – and therefore unpredictable – systems. They are grown indoors in a highly technical, highly mechanized process where natural inputs of nutrients and soil are replaced with chemical fertilizers and lightweight growing media. Sunlight shines through a sealed glass greenhouse and is augmented with specialized lighting. In an urban context, CEA is usually a rooftop greenhouse or the popular – though still rare – vertical farm.

CEA first found a commercial application in the Netherlands, which has a long history of using greenhouses to grow horticultural products and certain vegetables. With half of Europe's greenhouses (Encyclopedia of the Nations 2011), the Dutch are the world's largest exporter of greenhouse-grown products. As of 2006, the Netherlands's greenhouse-grown tomatoes, peppers, and cucumbers had an export value of €2.7 billion (Breukers, Hietbrink and Ruijs 2006).

The Dutch are the world's leader in controlled-environment agriculture, partly a result of their early adoption of CEA technologies. From 1980 to 1991, the Dutch phased out nearly all applications of methyl bromide – used to kill soil-borne pests – long before other industrialized nations began restricting its use. In the search for alternatives to methyl bromide, Dutch farmers successfully pioneered and refined the use of soil-alternative growing media for greenhouse-grown crops, effectively eliminating the need for soil (USDA 1996). Starting in the mid-1990s, this approach spread to North America. By 2003, 89% and 9% of commercially grown tomatoes for the fresh market in Canada and in the United States, respectively, came from greenhouses (Cook and Calvin 2005).

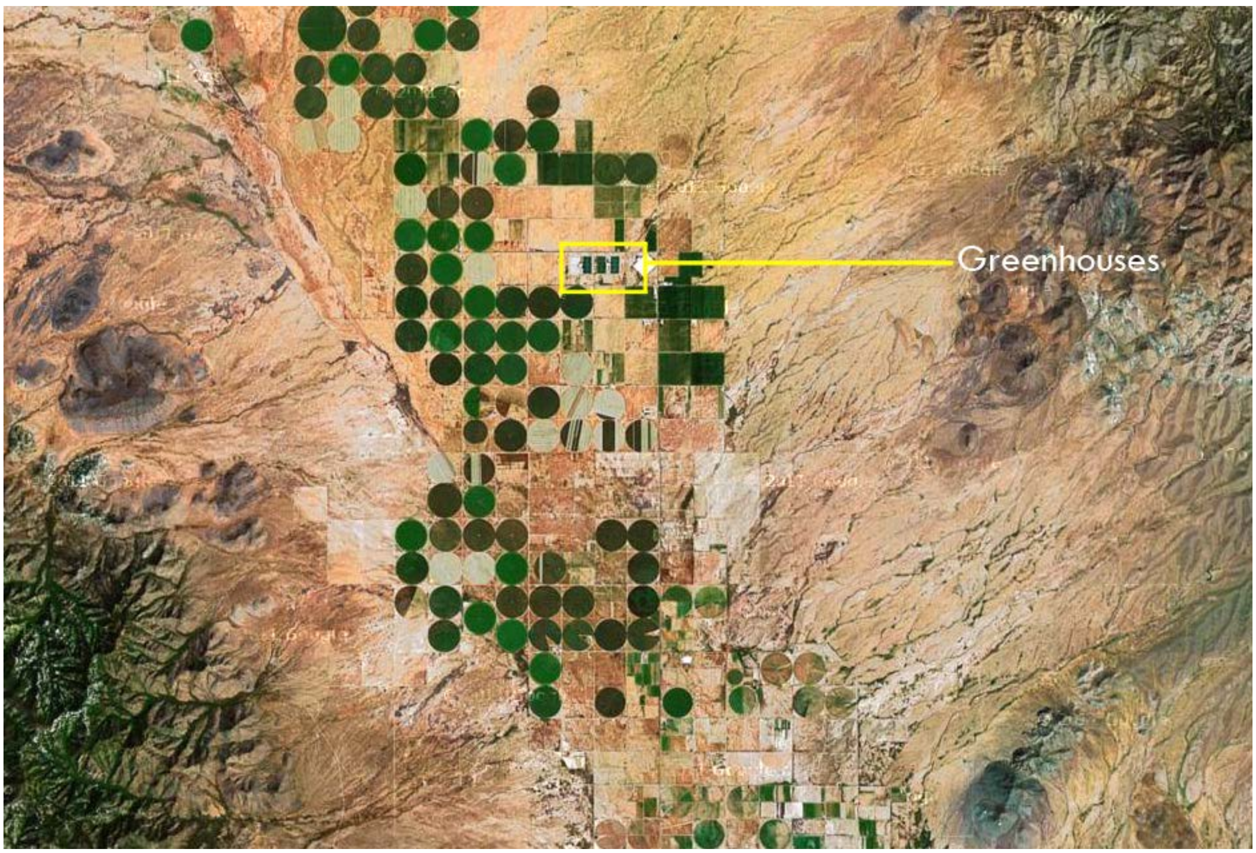

Figure 2 - Landscape of Southern Arizona agriculture. CEA greenhouses of "Euro Fresh Farms, Inc." in center. See zoomed in image of the greenhouses in Figure 3. Source: Google Earth.

Figure 3 - Images of controlled-environment agriculture. Left: The Westlands region of The Netherlands. Right: Euro Fresh Farms, Inc. in Wilcox, AZ. Source: Google Earth.

Controlled-environment agriculture is still a nascent form of commercial farming, but has broadened to include lettuce, other leafy greens, and strawberries. Given the obstacles of food production using urban air and soil, CEA will be the most viable option for urban farming at scale.

The Technologies of Closed-Environment Agriculture (CEA)

Various advanced food technologies are utilized in CEA in order to replicate the essential inputs required for food production. These technologies can be broadly assigned to two categories: 1) technologies that deliver water and nutrients in CEA, and 2) technologies that comprise the built environments of CEA.

<u>Nutrient and Water Delivery Systems</u>

- Hydroponics
- Growing Media
- Aquaponics
- Aeroponics

Building Technologies

- Rooftop greenhouses
- Vertical Farms
- Grow Lighting

These advanced technologies have the potential to dramatically alter the way in which foods are grown.

Hydroponics

Hydroponics is an artificial system which eliminates soil from plant growth by delivering nutrient-laden water directly to plant roots in constructed plant beds. Soil is open-environment agriculture's growing medium, but is not essential for plant growth (Barker and Pilbeam 2007). Soil provides drainage, airflow, housing for root systems, water retention, and protection against sudden environmental changes – all of which can be provided by alternative growing media (Traunfeld 2011). However, soil also imparts mineral nutrients necessary for plant growth into water (University of Hawaii 2012). In hydroponic systems, water is infused with these essential nutrients and fed to plants using a drip irrigation system that recirculates unused water (Hydrogarden Ltd. 2011).

Hydroponics has several benefits when compared to soil-based agriculture. Depending on plant and system type, 60-85% less water is used than in traditional agriculture (Mpusia 2006). The controlled indoor climate enables a year-round growing season and provides protection from insects, which greatly reduces the need for pesticides. Since plants are suspended and evenly spaced within growing tubes, ailing plants can be removed easily before disease spreads. Another benefit of hydroponics is the efficient use of nutrient inputs. The nutrient-laden water is controlled, reused, and treated within a hydroponic system, whereas soil-based agriculture results in nutrient run-off.

Primary drawbacks of hydroponic systems include high energy costs, limited plant variety, intensive human oversight, and the requirement of an uninterrupted power supply. Within artificial environments such as hydroponics, plants are sensitive to the slightest change and great effort must be spent to preserve their ideal growing situation. Lighting systems, planting trays, and water must be maintained continuously to avoid altering a complex equilibrium of variables needed for healthy plant growth (Guide To Hydroponics 2012).

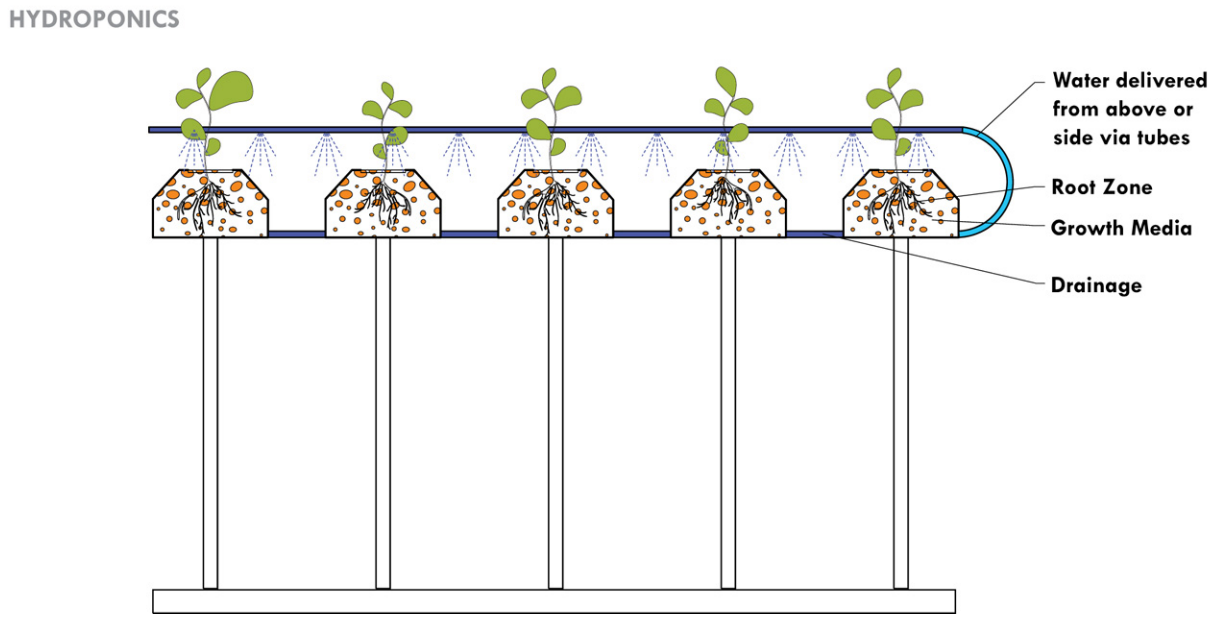

Figure 4 - Hydroponic channels using drip irrigation. Source: Author.

Growing Media

Growing media are non-soil alternatives used in CEA, especially in hydroponic systems. It is any material that can anchor plant roots for proper nutrient uptake. Growing media function similarly to soil, providing a foundation and structure for plant root systems. The quality of growing media is largely based on two characteristics: aeration (air porosity) and moisture retention. Moisture retention enables higher nutrient uptake and air porosity allows for drainage of excess moisture. In general, the physical structure and density of finer grain media are capable of higher water storage due to resistance to water flow. More loosely distributed or less dense media are better aerators, but allow water to flow too quickly through the medium.

Most growing media are composites of natural materials, with few exceptions such as polyurethane, which is a less preferred medium. The most common growing media are coconut fiber, perlite, vermiculite, and rockwool (woven fibers of stone). In many cases, growing media are composites made of more than one growing medium. This is usually the case because of unique material characteristics. Some materials have higher water retention and low porosity, while others have poor water retention and high porosity. In order to get optimal characteristics, growers mix materials that complement one another (Pasian 1997).

Growing Media	Texture/Air Porosity	Water Retention	Other Characteristics	Drawbacks
Coconut Fiber	Coarse/High	High, good for intermittent watering cycles	Waste material, contains hormones that stimulate roots to protect against fungus infestation	-
Clay Pellets	Fine/Low	High	-	
Sand	Coarse/High	Moderate	-	
Sphagnum moss	Moderate	High	-	
Gravel	Coarse/Moderate	Low	-	
Saw dust	Fine/Low	High	Waste material	-
Composted bark	Coarse/Moderate	Moderate	Waste material	
Lava rock	Coarse/High	Low	-	
Earthstone	Coarse/Moderate	Low	Waste material	
Coco shells	Coarse/Moderate	Low	Waste material	
Pumice	Coarse/High	Moderate	Balanced air porosity and water storage qualities	
Polystyrene (beads, foam)	Loose/Moderate	Low to moderate	Lightweight	Physical blending of polystyrene is a problem due to its extreme low density and non-wettability
Perlite	Coarse/High	Moderate	Volcanic glass, used as complement to vermiculite	Needs to be mined and heated up to 1600 degrees, dust from perlite is bad for your health, does not retain water well and dries very quickly
Vermiculite	Fine/Low	Too high	Requires 50/50 combination with perlite due to high water retention qualities	-
Rockwool	Moderate	High	-	Rockwool needs to be melted and spun into fine fibers

Figure 5 - Growth media comparison table. Compiled by author from various sources.[1]

Nutrient Film Technique

A more advanced form of hydroponics can position planting rows at a slight angle to let gravity provide drainage and to eliminate the need for a growing medium. With the nutrient film technique (NFT), plants are fed within and grow out of a tubular channel. A thin film of nutrient-infused water is continuously flowing along the channels housing the plants' root systems. These channels work best when shorter than 12 meters, since at longer lengths nitrogen levels begin to decline. Water flow rate can be up to 2 Liters/minute but works best at an average of 1 Liter/minute. The ideal slope of the tube for optimal flow along the roots is 1:100, but 1:40 is used more commonly to avoid the chance of water pooling around roots (ContainerGardening 2012).

Figure 6 - Nutrient film technique system. Source: Simply Hydroponics. (Photo analysis by author.)

Without the use of a growing medium, NFT further reduces material needs for plant growth, yet makes growing that much more dependent upon technological systems (ContainerGardening 2012). For example, a growth medium, such as rockwool, will help a plant survive longer if a power outage removes light or water.

Aquaponics

In aquaponic systems, CEA extends beyond fruits and vegetables to include fish and shellfish by raising aquatic animals in tanks (aquaculture) with plants in a separate hydroponic sub-system. Feed is introduced into the water for the aquatic animals, which in most applications have been fresh water fish – especially tilapia. Water is filtered to remove residual biomass, while the ammonia content, coming from fish gills and excreta, is converted to nitrogen and used to irrigate plants (Diver 2006). The water is pumped through a hydroponic subsystem where the plants absorb the nitrogen, making the water reusable for the aquatic animals (see Figure 7). Since the water recharged with nutrients by the aquatic animals, plants grown in this environment have a "free" nutrient source as compared with hydroponics alone (Diver 2006).

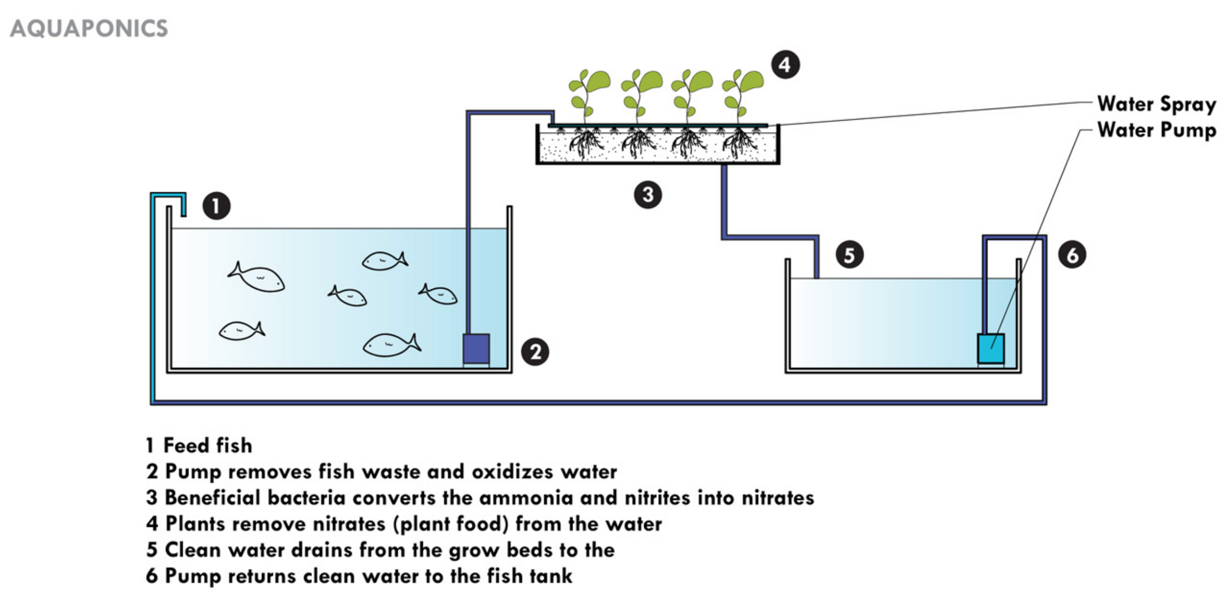

Figure 7 - Aquaponic process. Source: Author.

Aeroponics

Aeroponics, as the name suggests, optimizes the use of air in plant growth. Plants absorb nutrients through water, yet at the same time need ample oxygen and carbon dioxide. Soil and other growth media can provide this aeration and water carries a limited amount of oxygen. But poor drainage or a lack of porousness in the medium directly inhibits plant growth by limiting aeration. Rainforest orchids flourish atop canopies with their open-aired root systems nourished by the constantly humid environment of the forest below (Stoner, Rooting in Air 1983). Aeroponics operates similarly: instead of a stream of water, a mist of pressurized water droplets is continuously sprayed around the completely exposed surface area of an entire root system (Stoner, Aeroponics.com "How it Works" 2003). With aeroponics, the plants are still in rows similar to hydroponics, but hang in chambers instead of tubes (see Figure 8).

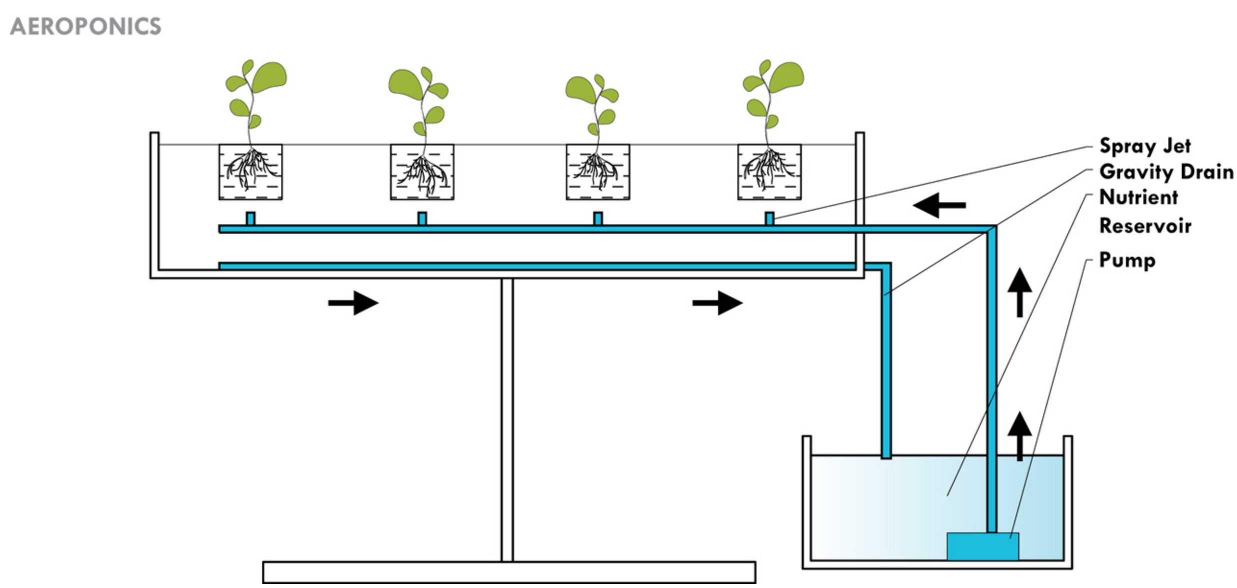

Figure 8 - Aeroponic process. Source: author.

With aeroponics, water droplets are sized, spaced, and applied to roots at levels that optimize a plant's need for oxygen, carbon dioxide, and water to maximize nutrient absorption. Achieving this optimization not only minimizes nutrient use per acre, but also decreases the amount of time it takes for a plant to grow. According to NASA's Small Business Innovation Research (SBIR) website, "(Aeroponic) food production technology will rapidly grow crops using 99% less water and 50% less nutrients in 45% less time," (NASA 2005).

Aeroponic research and development got a huge boost from NASA during the 1990s, as the agency sought ways to minimize water use while growing food during deep space missions in conditions of microgravity. A breakthrough study in 1996 examined cranberry roots grown aeroponically, where scientists were able to determine optimal nutrient uptake levels (Barak 1996). The study guided not only the further development of aeroponic technological systems, but it also highlighted aeroponic's role as a research tool, where a plant's life cycle and relative health can be easily monitored.

By 1999, NASA-led efforts were able to refine and test several designs of water droplet nebulizer technologies under varying pressures. Low mass polymers were developed for all aeroponic apparatus, simplifying the process of sterilization, keeping materials lightweight, and minimizing mineral build-up (Clawson 2012). Inflatable chambers for plant growing were also developed to include lightweight, portable options for extended time in orbit or on space stations. Aeroponics is NASA's preferred method for outer space-based agriculture, and since 2001, forms of the aeroponic technologies they have developed have became commercially available (NASA 2005).

Rooftop Greenhouses

A rooftop greenhouse is the most commonly employed CEA in urban and suburban environments. The business model associated with the form usually involves supermarkets and local restaurants contracting with a CEA company to buy greenhouse-grown tomatoes, peppers, cucumbers, lettuce, leafy greens, and herbs from a nearby rooftop greenhouse – often above the supermarket itself. The greenhouse is completely sealed off from the urban air and uses no urban soil, only hydroponic growing systems, with aquaponics and aeroponics added as needed. Using rooftops rather than ground level plots means maximizing sunlight for growing and utilizing space less likely to have competing land uses. BrightFarms, Inc., a New York City-based CEA company, recently contracted with local supermarkets to build the world's largest rooftop greenhouse at 100,000 square feet on top of a warehouse in Brooklyn. BrightFarms projects the greenhouse will have an annual yield of one million pounds of produce, which the supermarkets have agreed to buy for the next ten years (Foderaro 2012).

Figure 9 - Site of future rooftop greenhouse in Sunset Park, Brooklyn. Source: Eric Michael Johnson, The New York Times.

Vertical Farms

The concept of vertical farming is based on "stacking" CEA greenhouses on top of one another. Vertical farms are often portrayed in architectural renderings as skyscrapers dedicated to food production (see Figure 10). Popularized by ecologist Dickson Despommier in the early 2000s, vertical farming has become one of the most fashionable urban food technology concepts (The Economist 2010).

Figure 10 - Vertical farm rendering designed by Chris Jacobs. Source: MSNBC.

Moving beyond a rooftop greenhouse to storied greenhouses, encompassing several floors of an entire building, has proved elusive. A true vertical farm with commercial applications has yet to be built (The Economist 2010). Growing Power in Milwaukee, Wisconsin farms on more than one floor of a building, but that farm is designed for community empowerment (Goodman n.d.) and is not financially sustainable as a business model (Bomford 2010).

The greatest challenge for vertical farming is replicating sunlight. One ramification of a stacked greenhouse is that all plants will not receive direct natural light.   Extensive artificial lighting systems are needed to compensate for lack of sunlight. Given the high cost of electricity, this can be an incredibly expensive component of a vertical farm and one of the elements which renders vertical farming impractical. As a result, efforts continue to develop more energy efficient CEA lighting technologies (Alter 2011).

Grow Lighting

For vertical farms and other controlled-environment farms, lack of sunlight can be one of the most limiting factors and artificial lighting systems are required. Light emitting diodes are the most advanced and specialized lighting systems used in CEA. As opposed to incandescent or fluorescent lamps, LEDs can be designed to emit the precise light spectra necessary for photosynthesis, primarily blue and red light (Despommier 2011). Moreover, because LEDs produce less heat than more traditional lighting systems, indoor plant beds can be placed closer to the lights. In a vertical context, this means plant beds can be stacked closer together, enabling a more efficient use of energy and space.

However, the energy requirements of stacked lighting still pose limitations to the economic viability of vertical farms. Dr. Ted Caplow of New York Sun Works argues that vertical farming will only be practical if natural light can be harnessed (The Economist 2010). The firm Valcent

Figure 11 - LED lighting at the Jingpeng Plant Factory in Beijing. Source: Science Illustrated.

developed stacked hydroponic planting trays which move along rails to ensure even delivery of natural light to all plants. However, this system works only in a single-story greenhouse and does not address lighting issues of multi-story vertical farms.

Some researchers see the unpredictability of natural sunlight as a liability. PlantLab, a Dutch agricultural research group, claims sudden bright sunlight can destroy carefully engineered indoor environments and would rather rely on predictable, regulated, artificial lighting. PlantLab grows food crops in completely windowless environments, using red and blue LEDs.

Finding a solution to lighting will be one of the biggest obstacles to vertical urban farms. At the present moment, rooftop greenhouses, which rely primarily on natural light with some supplemental artificial light, are the most viable commercial application of CEA in urban settings.

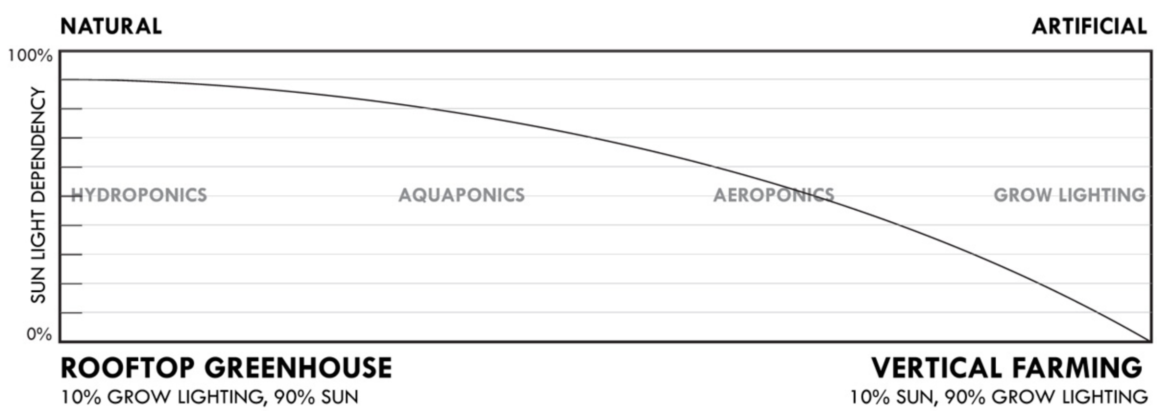

Figure 12 – Lighting use in different controlled-environment agriculture systems. Source: Author.

Controlled-Environment Agriculture: Cutting-Edge Applications

Even though commercial applications of CEA are not commonplace, there are examples of highly controlled growing environments in use for food production and other research applications.

Advanced CEA Food Production: South Pole Growth Chamber and PlantLab

As NASA continues to contemplate a mission to Mars and space colonization, it supports research efforts into food production in the most inhospitable environments. The South Pole Growth Chamber, designed by the University of Arizona's Controlled Environment Agriculture Center in conjunction with NASA, provides fresh vegetables daily to researchers living in the extreme cold of Antarctica using a hydroponic system (Controlled Environment Agriculture Center n.d.). Constructed in 2004 by the Raytheon Polar Services Company, with oversight from the National Science Foundation, the South Pole Growth Chamber is an advanced CEA farm. The Growth Chamber reduces the research facility's dependence on stored food supplies. The chamber symbolizes how far food production has moved along the natural to artificial gradient and offers a glimpse of what may evolve as limiting factors, such as climate change and population growth, continue to test agricultural production. Technology will enable people to grow food in environments where no plant could grow on its own.

Companies such as PlantLab mentioned previously, have fully embraced the potential of controlled-environment farming. Run by a team of four engineers, they express in their literature: "Not a ray of sunlight will enter the greenhouse of the future if it is up to us. Sunlight will be replaced with LED light plus Infrared. Plants will be given made-to-measure light, climate and nutrition," (PlantLab 2012). Their highly-monitored growing environment generates more than 160,000 reports per second, detailing all the specifics of humidity, CO2 concentration, light levels, and numerous other aspects of the indoor conditions. Their reliance on data and mathematics has enabled PlantLab to produce three times the amount of traditional food crops using only ten percent of the amount of water conventionally consumed (Saenz 2011). CEA is employing a new breed of farmers with different skill sets to oversee highly automated food technologies.

Figure 13 – Bell peppers grown indoors by PlantLab. Source: Natural Resources Conservation Service.

Advanced CEA Applications: Research, Biopharming, and GMO Seed Breeding

The biotechnology industry is an important player in developing CEA technology. CEA provides an isolated environment to allow for controlled development of transgenic crops and the use of plants for biopharming (Battelle Memorial Institute 2007). Pharmaceutical companies use CEA systems for drug production to avoid the risk of modified plants crossing over into conventionally farmed plants. Growing pharmaceutical demand combined with the risk of contaminating food supplies make CEA highly attractive to biotechnology firms – both as a laboratory to explore new drugs and as a method of production (Elbehri 2005). The University of Hanoi is using aeroponics to breed GMO potato seeds to eventually use in soil (Vietnam News Service 2009). This continued interest will foster more technological research.

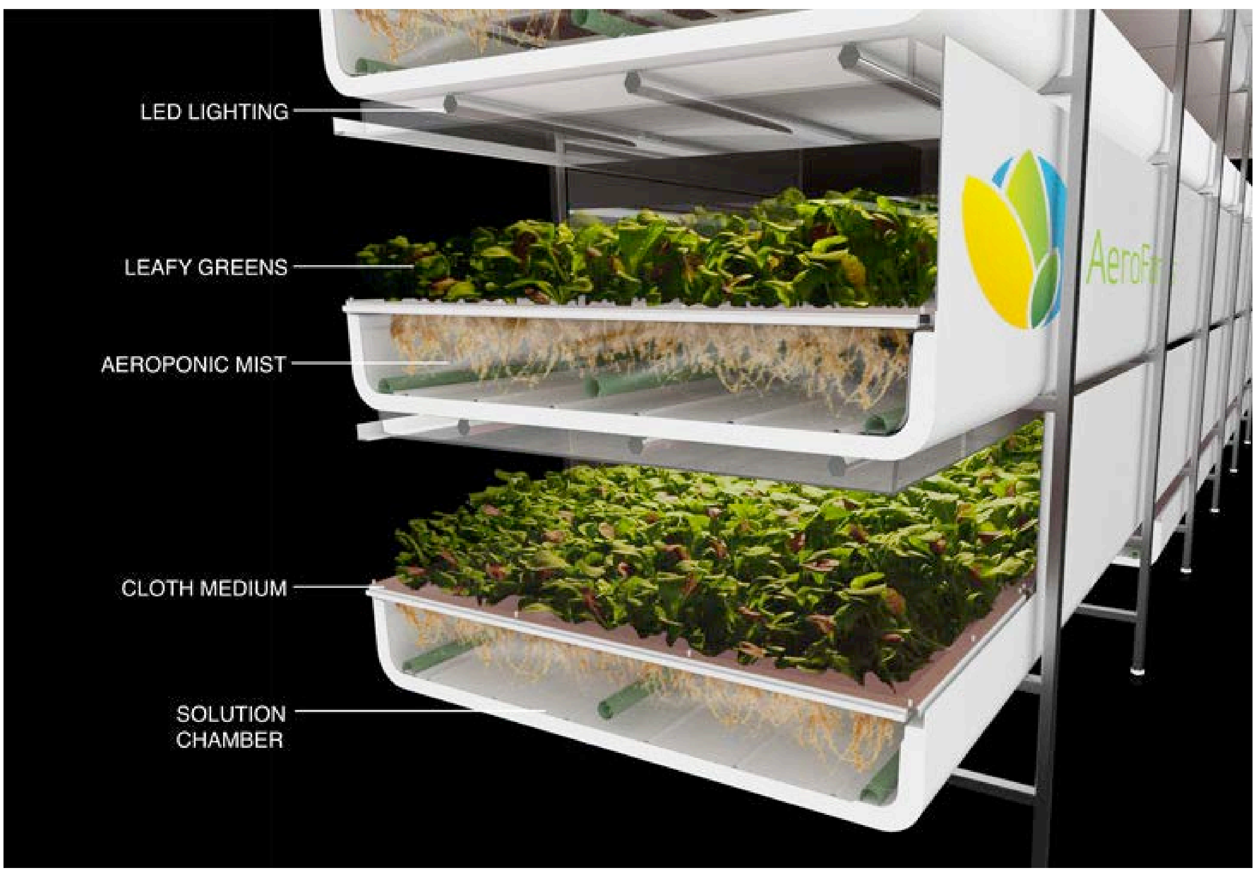

Figure 14 – Aeroponic system using grow lighting. Source: Inhabitat.

Open Environment Agriculture: Maximizing Yield in Compromised Environments

The constraints of open-air farming are changing rapidly. Constraints not only include soil contamination, but other environmental factors such as climate change, which makes weather systems more unpredictable and could have detrimental effects on yield. To guarantee maximum yield, the commercial agricultural industry has been invested in discovering the latest technologies in gene manipulation, which enable crops to tolerate extreme environments.

Resilient Crops: GMOs

Maintaining high yield is one of the most significant goals in agriculture. Low and freezing temperatures during growing seasons can dramatically decrease yield. For this reason, scientists have been identifying certain freeze-tolerant genes in plant species with the intent of introducing cold-tolerant genes in crops to allow for year-round crop production (Zhou 2005).

Freeze-resistant gene studies were completed by researchers in the Agri-Sciences Department of Tennessee State University. Antifreeze mechanisms in cold-tolerant plants were identified and isolated with the intention of introducing these genes to crops. The main plant species where the freeze-tolerant gene was found was the Pachysandra terminalis (Suping Zhou 2005). Cellular changes in plants were studied over various freezing temperatures, which led to the discovery of seven genes related to cold tolerance. In 2005, the next phase of development was to further analyze genetic transformation to test its possible function in crops for resistance to environmental temperatures. The cloned genes were to eventually be incorporated into cold sensitive crops, like tomatoes, to test their potential in improving cold tolerance (Zhou 2005) .

The company DNA Plant Technology developed an experimental, genetically-engineered cold-resistant tomato in 1991. The tomato included a modified gene from a breed of arctic flounder that would potentially allow the tomatoes to be more resistant to frost and cold storage. Due to activist uproar and opposition, these so-called "fish tomatoes" did not prove successful and the pursuit of a cold-resistant tomato was abandoned.

Salt-resistance is another category that has been explored by scientists and agriculturalists in order to genetically engineer crops that could resilient in high-salt conditions, such as seawater. The purpose in developing salt-tolerant crops is that up to 40% or 24.7 million acres of farmland in the United States is known to be damaged to some degree from salinity as a result of modern irrigation techniques (Zhou 2005).

In July 2001, scientists based out of the University of California shared their results of producing a salt-resistant tomato. They discovered that with manipulating the tomato's characteristics, they could have the salinity accumulate only in the leaves, leaving the fruit untainted and also maintain its original taste (Hong-Xia Zhang 2001). Their assumption was that genetically altering the plants by enhancing their ability to sequester sodium in their vacuoles could enable the transgenic tomato plants to use salty water for cell expansion and growth (Zhou 2005).

Efficient Water Techniques

Contrary to intuition, water research has not focused on genetic modification but on physical techniques of accumulating water in dry climates. In some regions such as Israel, they are looking to food production using wastewater filtration (Yosef Mizrahi 2002). Aquaponics is also a viable option that is being considered throughout the country (Appleton 2012). In Jordan, on 10 acres of flat desert land, the Jordan Valley Permaculture group is creating giant swales following the contour of the natural landscape. They are planted fruits trees and various fruit shrubs on the peaked land adjacent to the swale ditches in order to maximize what little water they had. This project proved that even with little water, these swales allowed for higher water retention over a longer period of time and produced higher yield.

Urban Agriculture: Limitations and Future Potential

While a plethora of advanced food technologies are currently being developed, some will be more practical, economical, and scalable in the future. Figure 15 compares nutrient delivery technologies to identify efficiencies and inefficiencies between conventional agriculture, hydroponic agriculture, and aeroponic agriculture. Both hydroponic and aeroponic systems are measured relative to the baseline of industrial agriculture's rural, soil-based production.

Aeroponics achieves remarkable water and nutrient efficiencies, yet is more likely to remain in the domain of NASA and biotechnology in the near future. Its costly and complex operating systems make mainstream application for food production unrealistic. Hydroponics, on the other hand, using drip irrigation and a growth medium, is less expensive and represents the most replicable form of CEA technology that can achieve some scale in urban food production.

	Conventional	Hydroponic	Aeroponic
Growing Media	Soil	Rockwool, Coconut Husks and Perlite	Air
Nutrients	Soil as source	Nutrients in H_20 solution	Nutrients in mist of water droplets
Water	Rain/Ground water as source.	Re-circulating flow of water	Re-circulating mist of droplets
Nutrients Needed	Baseline	50% of baseline	20% of baseline
Water usage	Baseline	15% of baseline	5% of baseline
Yield	Baseline	12x baseline	20x baseline
Environmental Factors	Pesticides and run-off	Few pesticides and *no* run-off; higher energy use	Few pesticides and *no* run-off; higher energy use
Complexity	Low	Medium	High

Figure 15 - Nutrient Delivery Comparison.[2]

Nevertheless, the narrow range of foodstuffs produced by all CEA technologies will likely be the greatest limiting factor to scale. Presently, grains, livestock, and root vegetables have not found commercially viable applications in CEA. CEA food production is limited to non-tuber and non-tree fruits and vegetables.

Figure 16 compares CEA building technologies to conventional farming to compare efficiencies and inefficiencies across a spectrum of characteristics. Rooftop greenhouses, while more expensive than conventional farms, are cheaper than vertical farms and have potential to scale up in the coming years, given the relative value communities might place on activating underutilized urban spaces and on locally grown food. Vertical farming has little hope registering an impact in the foreseeable future given its severe limitations financially, operationally, and environmentally.

	Conventional	Rooftop Greenhouse	Vertical Farming
Light	Sunlight	90% Sunlight; 10% Grow Lighting	10% Sunlight: 90% Grow Lighting
Yield per acre	Baseline	12x baseline	100x baseline
Energy Required[3]	Baseline	10x baseline	33x baseline
Real Estate Value	Baseline	12x baseline	400x baseline
Complexity	Low	Medium	High
Zoning	Easy	Difficult	Very difficult

Figure 16 – Controlled-environment agriculture building technologies. Compiled by author from various sources.[4]

The combination of hydroponics in a rooftop greenhouse will produce a product with cost certainty relative to open-aired, soil-based production. Climate change is likely to increase price volatility of conventionally grown food, which should increase the attractiveness of CEA production. Still, given the limited range and quantity of food produced in CEA, urban agriculture will be a very small player in resolving the global food supply challenges. The most meaningful innovations in food technology that increase production efficiency will happen in open-aired soil outside the urban core.

Conclusion: Urban Agriculture and Implications for Planners

As urban spaces are considered for commercial food production, the planning profession will experience the shift away from the notion that agriculture is a rural, place-based land use. Planners understand how to manage community gardening and weekend farmers' markets, yet few planners have addressed zoning changes to accommodate commercial applications of urban agriculture (Mukherji and Morales 2010). Cities will have to define the nature and extent of commercial farming activities within their limits and visualize how urban agriculture fits within mixed-use, densely populated environments. Community stakeholders will need to accept why sun rights mean something different to a commercial rooftop greenhouse operator than a hotel, and planners will have to do extensive analysis to determine preferred CEA siting zones. Since CEA is engineering-intensive and usually run by engineers, CEA proponents are likely to press municipalities for greater control over how urban farms are designed, constructed, and operated. As CEA achieves any kind of scale, cities with a strong regional agriculture presence may decline in economic prominence as they lose market share to formerly non-competing areas. Planners will need to design urban agriculture land use guidelines and educational programs to stay out in front of how this transition is perceived and managed.

[1] Compiled by author combining various estimates from several sources listed in the bibliography.
[2] Compiled by author combining various estimates from several sources listed in the bibliography.
[3] Based on a 2010 study comparing energy use between open-aired farming techniques, controlled-environment agriculture aquaponics using sunlight, and vertical farming using measures from the Growing Power's vertical farm in Milwaukee, WI (Bomford 2010).
[4] Compiled by author combining various estimates from several sources listed in the bibliography.

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