

Growing Up: An Exploration of the Past, Present, and Future of Hydroponics
and Controlled Environment Agriculture

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Eats 101 XL: Carolina Global Food Program

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Dedication

This paper is dedicated to my father, whose interest in engineering
and agriculture inspires this research and so much more.

Epigraph

"Water will be more important than oil this century"

—Boutros Ghali, 2003

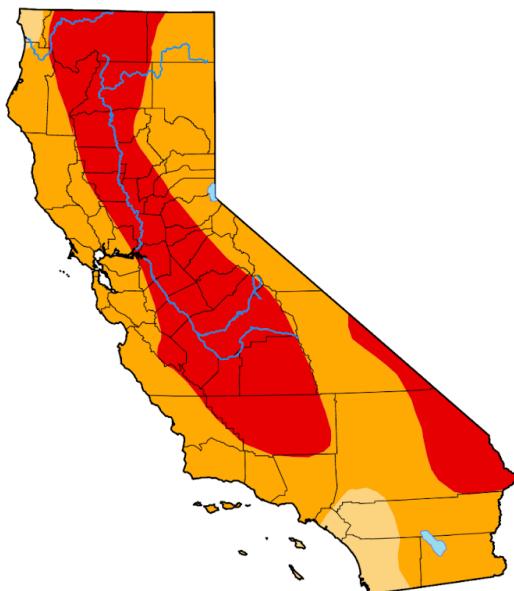
"Cultivators of the earth are the most valuable citizens. They are the most vigorous, the most independent, the most virtuous, & they are tied to their country & wedded to its liberty & interests by the most lasting bonds. As long therefore as they can find employment in this line, I would not convert them into mariners, artisans or anything else."

—Thomas Jefferson, *Letter to John Jay, August 23, 1785*

An Agricultural Pinch

In the midst of a year poised to find its place in the top ten hottest years on record, farmers and officials in California's agricultural belt are preparing for a grim year ahead. The US federal government announced in February of 2022 that the region, which produces roughly 25% of America's food, will not receive relief water from the Central Valley Project.

Over 95% of California is currently suffering from either severe or extreme drought, conditions under which "water levels are inadequate for agriculture, wildlife, and urban needs; reservoirs are extremely low and risk of "water theft" is high.¹



Map released: Thurs. April 21, 2022

Data valid: April 19, 2022 at 8 a.m. EDT

Intensity

None
D0 (Abnormally Dry)
D1 (Moderate Drought)
D2 (Severe Drought)
D3 (Extreme Drought)
D4 (Exceptional Drought)
No Data

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The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.

The U.S. Drought Monitor's categorization of California, as of April 21, 2022¹

Ernest Conant, regional director for the US Bureau of Reclamation, admitted that this year's drought may turn out to be worse than in 2021, when conditions got so bad that farmers

¹ National Drought Mitigation Center University of Nebraska-Lincoln. (n.d.). *U.S. Drought Monitor*. | U.S. Drought Monitor. Retrieved April 24, 2022, from <https://droughtmonitor.unl.edu/CurrentMap/StateDroughtMonitor.aspx?CA>

were forced to abandon cultivation on hundreds of thousands of acres of plowed and harrowed cropland. “It’s devastating to the agricultural economy and to those people that rely on it,” said Conant, “but unfortunately we can’t make it rain.”²

As populations increase and demand rises for fresh water, a warming climate means less supply to meet those needs. Devastation from water scarcity spans well beyond California, and 40% of the world population lives in water-stressed regions.³ Global metropolises including Rome, Cape Town, Chennai, and Lima have been increasingly forced to ration water. The Middle East and North Africa have only 1.4% of the world’s renewable fresh water despite having 6.3% of the world’s population.⁴ Water scarcity plays an increasingly large role in geopolitical tensions, with countries nervous of trends that point towards devastation, famine, and even war.

The Grand Ethiopian Renaissance Dam, a hydroelectric dam being built near the source of the Nile River, has escalated tensions between Ethiopia, Egypt, and Sudan over how much the dam will impact water availability in downstream countries.⁵ More than 10 dams built along the Mekong river in China have downstream countries including Myanmar, Laos, Thailand, Cambodia and Vietnam worried about their larger neighbors’ ability to control their water access. These

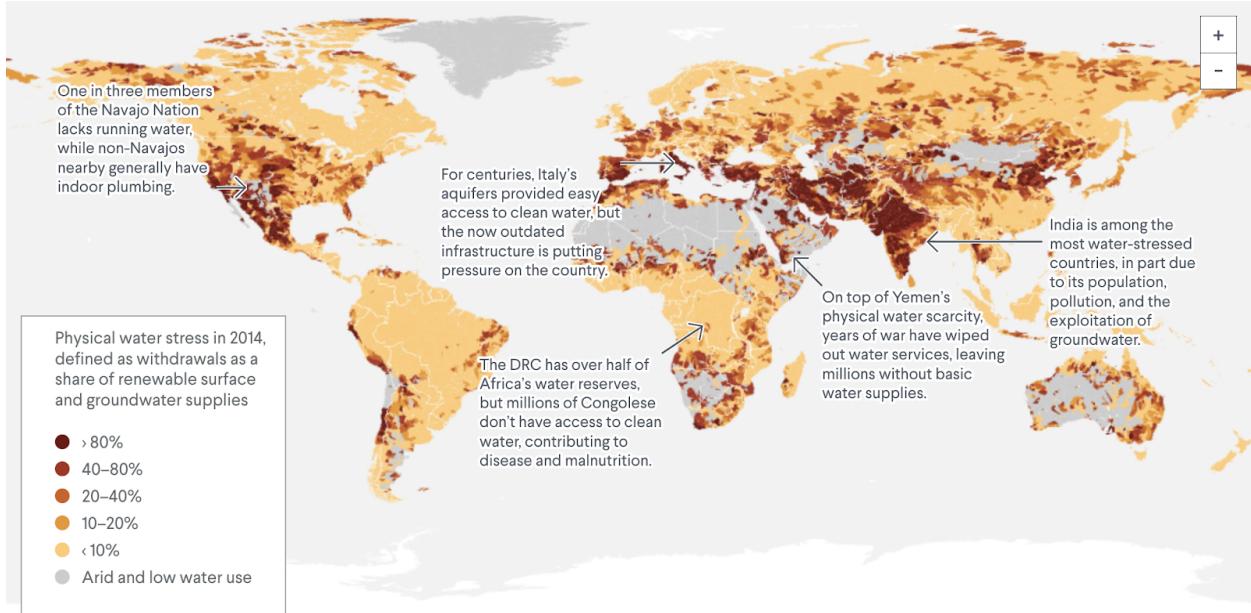
² Guardian News and Media. (2022, February 24). ‘we can’t make it rain’: California farmers left out to dry as US government allots no water. The Guardian. Retrieved April 24, 2022, from <https://www.theguardian.com/us-news/2022/feb/23/rain-california-farmers-us-government-drought-water>

³ BBC. (n.d.). How water shortages are brewing wars. BBC Future. Retrieved April 24, 2022, from <https://www.bbc.com/future/article/20210816-how-water-shortages-are-brewing-wars>

⁴ Finding the balance: Population and water scarcity in the Middle East and North Africa. PRB. (n.d.). Retrieved April 24, 2022, from <https://www.prb.org/resources/finding-the-balance-population-and-water-scarcity-in-the-middle-east-and-north-africa/>

⁵ Mbaku, J. M. (2022, March 9). The controversy over the Grand Ethiopian Renaissance Dam. Brookings. Retrieved April 24, 2022, from <https://www.brookings.edu/blog/africa-in-focus/2020/08/05/the-controversy-over-the-grand-ethiopian-renaissance-dam/>

worries heightened when, in 2018, water levels in the Mekong River fell to their lowest point in over 100 years.⁶



Darker shaded areas have more physical water stress; but a myriad of factors, including infrastructure, governance, and population, all contribute to water availability.⁷

The World Economic Forum has ranked water crises in the top five global risks for nearly every year since 2012, including a severe 2017 drought across Africa and the Middle East that displaced over 20 million people due to food shortages and conflict.³

Globally, 70% of freshwater is used for agriculture.⁸ Irrigation accounts for a sizable chunk of this, which has proven in the last few decades to be a strong driver of increased crop yields.⁹ It

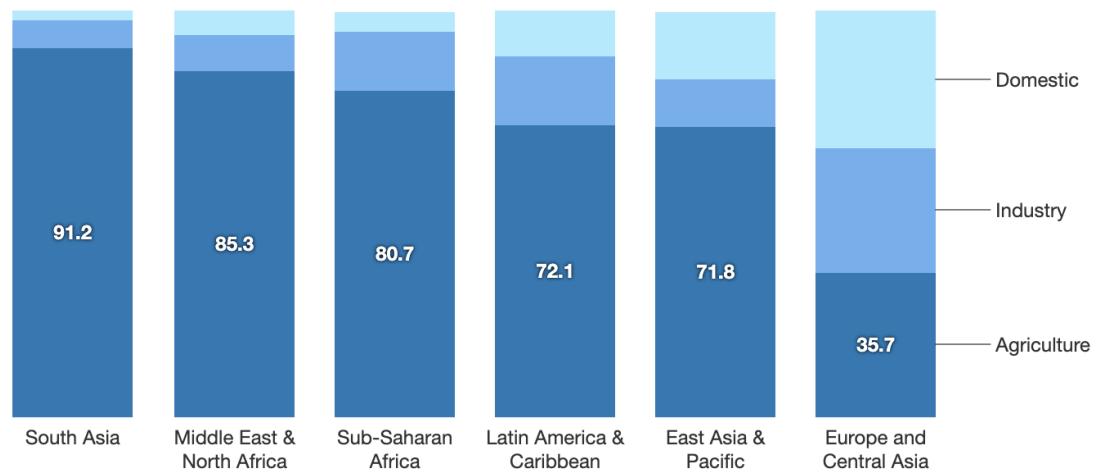
⁶ Eyler, B. (2020, April 22). *Science shows Chinese dams are devastating the Mekong*. Foreign Policy. Retrieved April 24, 2022, from <https://foreignpolicy.com/2020/04/22/science-shows-chinese-dams-devastating-mekong-river/>

⁷ Felter, C., & Robinson, K. (n.d.). *Water stress: A global problem that's getting worse*. Council on Foreign Relations. Retrieved April 24, 2022, from <https://www.cfr.org/backgrounder/water-stress-global-problem-thats-getting-worse>

⁸ World Bank. (n.d.). *Chart: Globally, 70% of freshwater is used for Agriculture*. World Bank Blogs. Retrieved April 24, 2022, from <https://blogs.worldbank.org/opendata/chart-globally-70-freshwater-used-agriculture>

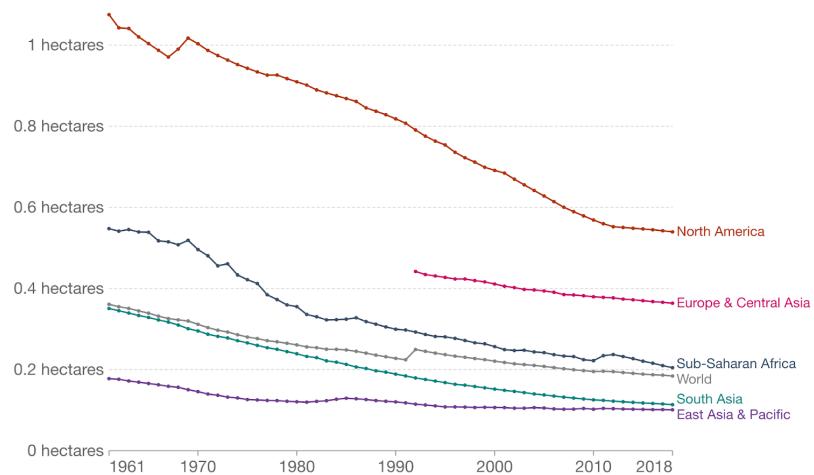
⁹ Ritchie, H., & Roser, M. (2017, November 20). *Water use and stress*. Our World in Data. Retrieved April 24, 2022, from <https://ourworldindata.org/water-use-stress>

is most common in some of the world's most arid regions, including the Mediterranean and Middle East.



Share of freshwater withdrawals by sector (%), as of 2014⁸

In addition to the global water crisis, the last 50 years have seen the global population more than double. With a finite supply of arable land, farms are forced to produce more yield on the same amount of land, and consumers are being corralled towards plant-based foods which offer a lower land footprint.



Arable land use per person over time, by continental region¹⁰

¹⁰ Ritchie, H., & Roser, M. (2013, November 13). *Land use*. Our World in Data. Retrieved April 24, 2022, from <https://ourworldindata.org/land-use>

In addition to population and water pressures on agriculture, numerous recent global catastrophes have exposed the fragility of our complex intercontinental supply chains. Nearly \$10 billion of trade per day was brought to a halt when the Ever Given, one of the largest container ships ever built, got stuck in the Suez Canal for nearly a week.¹¹ The COVID-19 pandemic led to movement restrictions for workers, volatility in consumer demand, closures of shipping and food production facilities, restricted trade policies, and financial pressures on the food supply chain.¹²

The recent Russian invasion of Ukraine has disrupted the global trade of fertilizer, animal feed, and sunflower oil. It's estimated that nearly 12% of the total calories traded in the world are sourced from Russia and Ukraine,¹³ and with Russia under sanctions and Ukraine in the midst of an invasion, the supply of these crops and fertilizers have stalled.¹⁴

Global supply chain issues create not only short term shortages and waste but long term distrust towards an unstable international trade system. As water shortages, arable land, and supply chain breaks cause problems for agriculture and food production across the globe, one agricultural method has cropped up as a potential alleviator: controlled environment hydroponic agriculture. Before diving too deep into recent adaptations, I'll overview the origins of hydroponics and its journey towards relevance in modern agriculture.



¹¹ Yee, V., & Glanz, J. (2021, July 17). *How one of the world's biggest ships jammed the Suez Canal*. The New York Times. Retrieved April 24, 2022, from

<https://www.nytimes.com/2021/07/17/world/middleeast/suez-canal-stuck-ship-ever-given.html>

¹² Serpil Aday, Mehmet Seckin Aday, Impact of COVID-19 on the food supply chain, Food Quality and Safety, Volume 4, Issue 4, December 2020, Pages 167–180, <https://doi.org/10.1093/fqsafe/fyaa024>

¹³ Glauber, J., & Laborde, D. (n.d.). *How will Russia's invasion of Ukraine affect global food security?* Ifpri.org. Retrieved April 24, 2022, from

<https://www.ifpri.org/blog/how-will-russias-invasion-ukraine-affect-global-food-security>

¹⁴ Barbaro, M. (n.d.). *How the war in Ukraine is creating a global food crisis*. The New York Times. Retrieved April 24, 2022, from
<https://www.nytimes.com/2022/04/05/podcasts/the-daily/ukraine-russia-food-supply.html>

An Introduction to Hydroponics

Hydroponics, at its most fundamental level, is the practice of growing plants in water rather than soil. Its roots date back thousands of years with illustrious examples of ancient civilizations employing the practice at the Hanging Gardens of Babylon, floating gardens in China, ancient Egyptian hydroponic farms along the Nile River, and the Aztec chinampas in the valley of Mexico.¹⁵



The Aztecs cultivated crops such as vegetables, flowers, and maize on chinampas, rafts of rushes and reeds¹³

Modern US interest in hydroponics emerged in the 1930s, when Dr. William Frederick Gericke from UC Berkeley began experimenting with a theory that the healthy and sustained

¹⁵ Folds, E. (2018, March 23). *The history of hydroponics*. Medium. Retrieved April 24, 2022, from <https://evanfolds.medium.com/the-history-of-hydroponics-99eb6628d205>

cultivation of many crops does not require soil itself but, rather, the nutrients within the soil. By emulating the nutrient make-up of soil, he and his team cultivated over 1000 lbs of tomatoes including vines of over 25 feet using a shallow basin with nutrients and water.¹⁶ The nutrient solution went on to inspire a modern take on what hydroponics could be: a cultivation system divorced from soil and scientifically contrived to match the requirements of whatever best suits the crop.

Indoor hydroponic cultivation took off with cannabis in the 1980s, when the advent of High Intensity Discharge indoor grow lighting emerged at a time when outdoor growers faced concerns of herbicides and an aggressive government crackdown on cultivation of the plant.¹⁷ Isolation from the natural environment meant liberation from both human and wild pests, evasions of toxins in the soil that could poison the marijuana, and year-round growth.¹⁸

The indoor cultivation of cannabis continued to gain popularity in the following decades, propelling the industry forward as farmers demanded cheaper and more efficient grow lights, pumps, and grow mediums. Today, over 80% of cannabis grown in the US is grown indoors.¹⁹

Just as cannabis growers sought to avoid the dangers of the natural garden, experimental farmers came to realize indoor hydroponic agriculture as a cultivation method that would isolate them from agricultural issues such as variable climate, pests, weeds, and a reliance on fertilizing soil year after year. Most other crops being lower in value, however, high costs of energy and lighting staved off many agricultural players for decades for one simple reason: indoor agriculture did not make financial sense.

¹⁶ *Hydroponics History*. Hydroponics PSU. (n.d.). Retrieved April 24, 2022, from <https://sites.psu.edu/hydroponicspsu/what-are-hydroponics/hydroponics-history/>

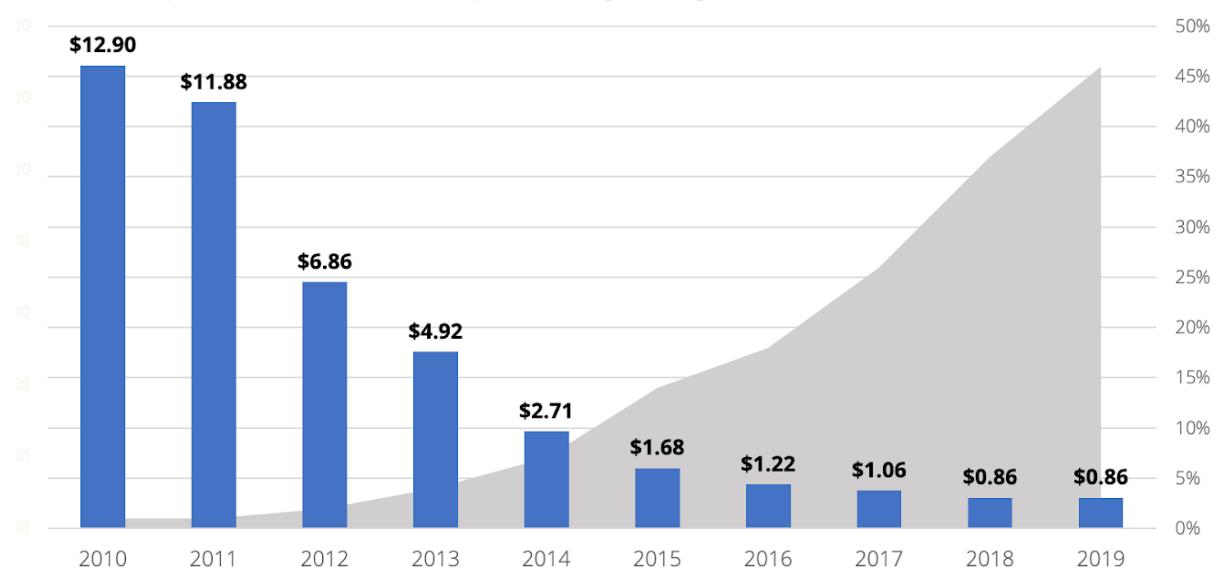
¹⁷ St. Pierre, A. (2019, September 25). *A timeline of Cultivation Technology*. Cannabis & Tech Today. Retrieved April 24, 2022, from <https://cannatechtoday.com/cultivation-tech/>

¹⁸ Lajeunusse, S. (2021, December 29). *Cannabis may contain heavy metals from the soil*. Futurity. Retrieved April 24, 2022, from <https://www.futurity.org/cannabis-heavy-metals-2674872-2/>

¹⁹ Fertig, N., & Bade, G. (n.d.). *An inconvenient truth (about weed)*. POLITICO. Retrieved April 24, 2022, from <https://www.politico.com/news/2021/08/10/weed-cannabis-legalization-energy-503004>

Methods and technology continued improving over time, but it wasn't until the mid 2010s, when leaps in LED innovation made farmers revisit indoor hydroponics as a potential alternative for cultivation. LED lighting had become economically viable and presented the opportunity to cut energy consumption by 85%, increase the lifespan of bulbs to 25 years, and emit much less heat than fluorescent or incandescent lights.²⁰

(US\$ cost per kilolumen / LEDs as a percent of global lights sold)



LED sales volume increasing over time as cost fall²¹

Thus, the range of crops that were financially viable to grow hydroponically indoors expanded to modern day staples such as leafy greens, herbs, and tomatoes. After several decades of optimizing methods, the drop in lighting costs tipped the scales for hydroponic use cases from small-scale passion projects to commercially scalable business models, leading to thousands of hydroponics farms sprouting up across the globe.

²⁰ Popovich, N. (n.d.). *America's light bulb revolution*. Retrieved April 24, 2022, from <https://www.nytimes.com/interactive/2019/03/08/climate/light-bulb-efficiency.html>

²¹ US Department of Energy. (2021, September 28). *Cost of LED lighting dropped 15-times as volumes increase*. Freeing Energy. Retrieved April 24, 2022, from <https://www.freeingenergy.com/facts/led-bulb-light-cost-price-historical-decline-g213/>

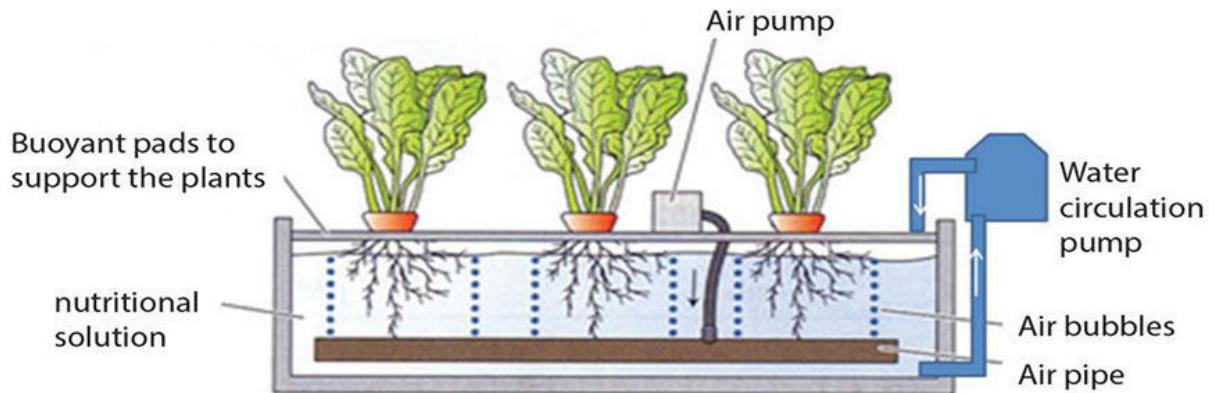


Diagram of a basic hydroponics system²²

While the foundations behind hydroponics remain, the large-scale hydroponics we see today is unrecognizable to the Aztec chinampas in the valley of Mexico. Complete isolation from the outdoors and integrations of technology such as sensors, pumps, and indoor lighting have culminated in a new term to describe this style of farming: Controlled Environment Agriculture (CEA).

CEA is a method of hydroponic cultivation in which plants are grown indoors with controlled variables such as temperature, humidity, light wavelengths (simulating sunlight at various times of the year), pH, and nutrients. In a controlled environment, farmers can optimize conditions for any given crop's optimal nutrient levels, lighting, humidity level, and so on.

²² *Hydro-, aqua-, and Aeroponics*. Terrascope 2024. (n.d.). Retrieved April 24, 2022, from https://terrascope2024.mit.edu/?page_id=313



A photo from Sky Greens, a modern CEA vertical hydroponics farm in Singapore²³

Further, the ability to reduce waste is high in a controlled environment. Water, for example, can be targeted directly to the roots and recirculates through a system with low evaporative loss. Growing from water chambers lends itself to vertical stacking, multiplying the yield per acre by as many levels as the vertical farmer chooses to build. Compared to traditional agriculture, CEA requires up to 95% less water and can produce 25 times as much per acre.²⁴

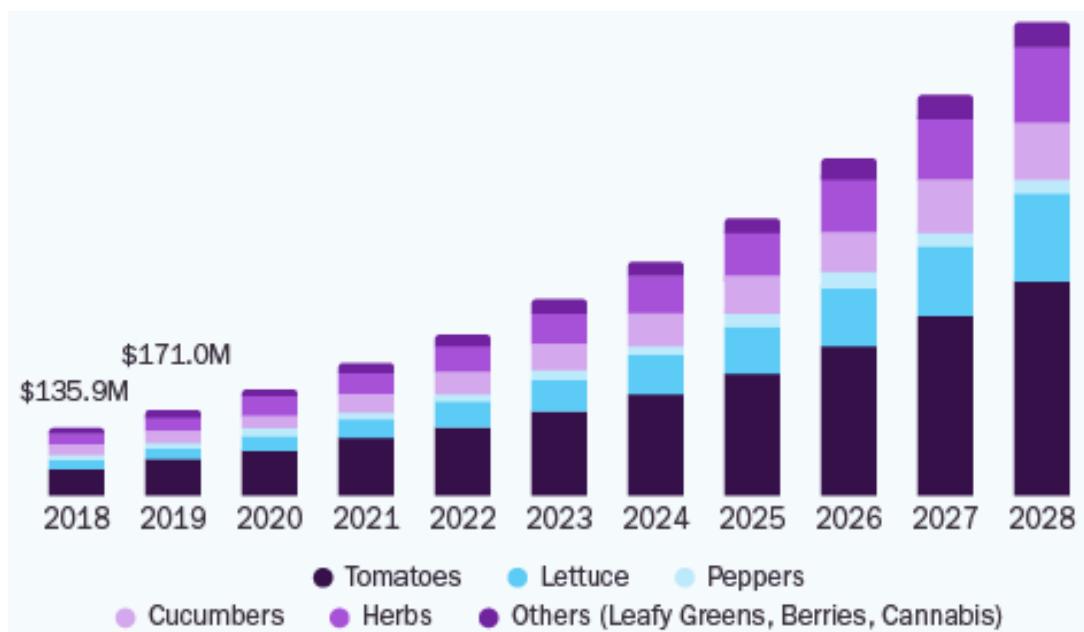


²³ Sky Greens. (2017, May 15). Retrieved April 24, 2022, from <https://www.skygreens.com/>

²⁴ Bailey, M. (n.d.). *Why controlled environment agriculture (CEA) is the future of farming*. Dantherm Group. Retrieved April 24, 2022, from <https://www.danthermgroup.com/en-gb/calorex/why-controlled-environment-agriculture-cea-is-the-future-of-farming>

Modern Commercial Hydroponics

The US hydroponics market has nearly tripled over the past 5 years, and industry analysts project the industry to eclipse \$1 billion by 2028, driven largely by an increase in the market share of tomatoes.²⁵ Additionally, investment in CEA startups has dramatically increased year over year.²⁶



U.S. Hydroponics Market Size from 2018-2028, by crop²⁷

Investors in CEA are betting on overcoming current cost hurdles that stand in the way of reaching the promised land of automated agriculture. Hydroponics companies still struggle with high costs of startup, labor, and energy. Nearly 50% of indoor farms fail to make a profit and farms

²⁵ Hydroponics market share, research 2025: Industry growth report. Hydroponics Market Share, Research 2025 | Industry Growth Report. (n.d.). Retrieved April 24, 2022, from <https://www.millioninsights.com/industry-reports/hydroponics-market>

²⁶ Hullett, J., & Sparks, B. D. (2021, July 22). Why investors are putting their money toward controlled environment growing. Greenhouse Grower. Retrieved April 24, 2022, from <https://www.greenhousegrower.com/crops/why-investors-are-putting-their-money-towards-controlled-environment-growing/>

²⁷ Hydroponics market size & share report, 2021-2028. Hydroponics Market Size & Share Report, 2021-2028. (n.d.). Retrieved April 24, 2022, from <https://www.grandviewresearch.com/industry-analysis/hydroponics-market>

are under constant pressure to drop the cost of production to a level where their prices can compete with traditional farms that use the sun for light, earth for soil, and rains for water.²⁸

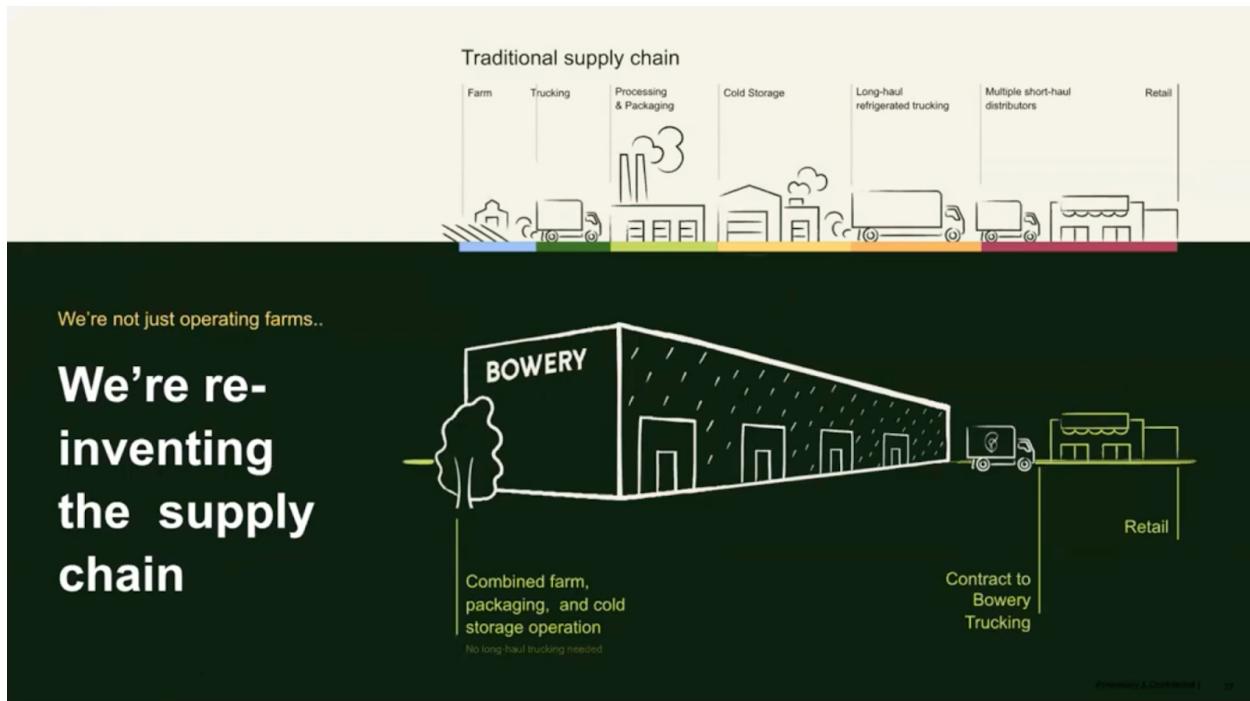
Labor stands out to many CEA companies as the cost variable to focus on, as it accounts for nearly 50% of operating costs.²⁹ Innovations in automation and robotics offer a promising outlook on the potential to replace maintenance and harvesting labor at scale, and the result is an industry race towards incorporating tech to optimize and automate as much of the cultivation process as possible.

In the face of investor scrutiny over losses, CEA giant AppHarvest recently divided operations into three internal branches, one of which (TechCo) will develop the company's key technologies, including "proprietary FarmOps, robotic harvesting capability, and AI/machine learning for growing—as well as the potential to develop a new revenue stream through licensing of CEA technology to global operators."³⁰ That's to say, one of the three main pillars of AppHarvest is entirely dedicated to using data and machines to cut costs and improving crop yields.

²⁸ Agrilyst. (2018, October 1). *Agrilyst releases Third State of Indoor Farming Survey*. Produce Grower. Retrieved April 24, 2022, from <https://www.producergrower.com/article/agrilyst-state-of-indoor-farming-survey/>

²⁹ *Economic feasibility*. Terrascope 2024. (n.d.). Retrieved April 24, 2022, from https://terrascope2024.mit.edu/?page_id=314

³⁰ *AppHarvest Q2 2021 results*. AppHarvest. (n.d.). Retrieved April 24, 2022, from <https://investors.appharvest.com/news-releases/news-release-details/appharvest-announces-q2-2021-results-plans-new-holding-company>



Bowery, another CEA giant, demonstrates their plans for full production integration by comparing their food production process to the production and supply chain status quo³¹

CEA giants are working towards facilities where robots manage the process from start to finish: the planting, farming, harvesting, transport, storage, and packaging. Even the delivery to retail, at some point, will likely be a task for a machine.



Criticism

Unlike other well known advances in agriculture such as fertilizers or GMOs, hydroponics has perplexed critics as its benefits go beyond increasing crop yields and financial savings. That said, the industry has found pushback from naysayers citing practicality issues, such as financial feasibility and scalability beyond lettuce, herbs, and tomatoes.

³¹ *How To Invest In Controlled Environment Agriculture With Confidence*. Bowery Farms. (n.d.). Retrieved April 24, 2022, from <https://www.youtube.com/watch?v=acovNsx8tYw>

In the past, critics have called out a lack of taste from hydroponically grown produce and worry about a future where such a standardized grow process leads to mono-tasting crops. In the past few decades, numerous experiments have shed quite a bit of light on the factors that create taste, and learnings are applied at most large-scale CEA farms. Inputs, including light exposure, temperature, and nutrients consumed in the growing process all influence flavor, and given that these are controllable variables in CEA, the process actually has the capability of providing tastier crops on a more consistent basis.³² Beyond the cultivation process, the 48 hour time horizon from hydroponic farm to table ensures peak freshness of the produce.



Growing Forward

CEA is taking hold in a handful of agriculture niches, but it's nowhere close to replacing the entirety of traditional agriculture. The commercial indoor hydroponics industry is erupting but finds itself constrained by three main bottlenecks:

1. Costs, particularly those which relate to labor and energy
2. Machinery capabilities and AI, which needs data and training to produce helpful models
3. Cost-effective crops to produce, farms currently find it financially burdensome to grow crops beyond leafy greens, tomatoes, herbs, strawberries, and a few other crops

These constraints limit the purview of CEA today, but they all share a golden commonality: the rate of change on these constraints has them moving in the direction CEA needs.

Lighting continues to get cheaper, more efficient, and more tailored for indoor growing. This translates to lower overhead costs in purchasing lights, lower operational costs in increased efficiency, and higher output per dollar spent on lighting in specialized lighting. Additionally, the

³² Dupuis, A. (2021, August 24). *Hydroponic produce: What the foodies are saying*. Eden Green Technology. Retrieved April 24, 2022, from <https://www.edengreen.com/blog-collection/hydroponic-produce-what-the-foodies-are-saying>

US energy grid is shifting its weight towards renewables, and those renewables are becoming cheaper and more efficient.³³

Innovation in machinery benefits from relevant discoveries driven by a variety of industries, from self-driving cars to insurance and hospital systems. A growing indoor agriculture sector means that development of these machines will be increasingly tailored towards the needs of CEA. Machine learning and artificial intelligence are similarly cross-functional, meaning that discoveries shared in open-source libraries like TensorFlow could very quickly benefit the production at AppHarvest. These systems will become more effective and efficient over time, and stand to replace a substantial portion of operating costs in labor.

CEA is just getting started with respect to the growing environment iteration process. Identifying optimal parameters/additives, quantities, and methods of growth/application will be key to optimizing yield. Additionally, further research on the soil microbiome and plant hardiness will continue to inform environment optimization for taste and productivity. Crops like corn and wheat do not currently make sense for CEA, and, many argue never will. Nearly every plant can grow hydroponically, but various aspects of the cultivation process, such as pollination and plant architecture, make some crops less suitable. While some critics view this as the limiter of hydroponics, I have an inkling that if all other variables point to CEA, the gene-editing field will see a lucrative draw to tailor the development of plant architecture towards hydroponic conditions.

³³ Marcacci, S. (2022, April 14). *Renewable energy prices hit record lows: How can utilities benefit from unstoppable solar and wind?* Forbes - Energy Innovation: Policy and Technology. Retrieved April 24, 2022, from <https://www.forbes.com/sites/energyinnovation/2020/01/21/renewable-energy-prices-hit-record-lows-how-can-utilities-benefit-from-unstoppable-solar-and-wind/>



Potential for growth based on the rate of change of key factors, Agritecture²⁹

While outdoor agriculture faces environmentally prohibitive issues such as volatility of climate and soil, indoor agriculture faces issues of technology and efficiency. Outdoor agriculture cannot compete with CEA's ability to grow locally year-round, produce quick yields, optimize efficiency of space, conserve water usage, and establish consistency in production.



A Post-growth Society

Given the rates of innovation of CEA's key constraints, I find it reasonable to imagine a future where CEA is tasked with a large share of our agriculture. As such, I will use the second half of this paper to discuss potential societal changes that may occur from these constraints being taken to the extremes.

These extremes are aggressive assumptions. Forecasting the development of well-known technology is tough enough, let alone gene-editing on plants for purposes barely explored before. Predicting things like how the influx of capital to this space will accelerate innovation in this innovation is difficult, but trends outlined above lead me to believe these assumptions are possible.

While the specifics of timelines, crop breakdowns, and market share are beyond my knowledge, I have a handful of eventualities that I can foresee coming to fruition and, given that they do, I'm curious about where that would put us as a society. Those eventualities are the following:

1. Costs of lighting and energy continue to fall out of the picture. Hydroponics farms source energy from clean energy sources and lighting to grow in hyper-efficient conditions. As these costs fall, CEA operations expand their breadth into more crops.
2. Operational cost of labor falls to near-zero. Development in software and hardware eliminates human involvement in the cultivation process: everything from planting the seeds to harvesting the ripe produce is done by machines.
3. Research and development has broadened the range of crops suitable for indoor growth. Further, research in soil has allowed hydroponically grown food to emulate soil cultivation in any part of the world.

As these predictions come to fruition, I would expect a variety of changes. Low costs and industry knowledge would make CEA the industry standard for growing the majority of cannabis, herbs, vegetables, tomatoes, and mushrooms.

Aforementioned benefits of CEA are brought to an extreme: produce is consistent, cheap, and local. Transportation time and costs disappear. Hundreds of millions of hectares are freed from the reigns of agriculture. Efficiency in water use frees up freshwater for other uses. Runoff and environmental damage from non-organic compounds such as pesticides, herbicides, and fertilizers falls drastically.

The largest question, then, becomes just how much of agriculture CEA can overtake. With costs diminished and efficiency optimized, the only prohibitor becomes what is physically and methodologically possible. In order to grow, CEA is thus faced with two options: either develop

methods to grow more important crops, such as corn, soy, and wheat, or explore plant derivatives that can drive up demand for a currently hydroponically efficient crop, such as lettuce.

With respect to the first option, although most large-scale hydroponics currently focus on leafy greens, herbs, cannabis, and tomatoes, researchers are exploring hydroponic production of vegetables such as beans, peas, onions, cucumbers, peppers, radishes, and carrots. Fruits, including strawberries, watermelon, berries, and grapes are similarly garnering more attention from experimenters. Even trees such as mini cherry trees, banana trees, nut trees, and dwarf apple trees can be grown hydroponically, albeit far removed from a cost-competitive nature.

If efficiency and scale of hydroponics ramps up, the method could compete with outdoor agriculture on staples such as soybeans. Leaps forward in sugar, corn, cacao, coffee, soybeans, or rice would likely lead to massive investment in CEA. Particularly with players such as NASA investing in hydroponics soybean production, I foresee potential to make breakthroughs on a crop that currently seems nonsensical to grow indoors. Crop by crop, research and development teams will discover feasible methods and variations for CEA.

The second possibility entails creating value from easily growable produce. Corn, the most abundant crop in North America, is a great example of this. Nearly 45% of corn becomes animal feed, 44% becomes ethanol, and only 10% becomes human food. Within the share of corn used for human food, roughly a third is converted into high-fructose corn syrup.³⁴

If hyperproductive CEA farms can grow lettuce at a nearly costless rate, the opportunity arises for humans to discover a use for it. Lettuce is just one example, but it shows promise in derivative oils addressing sleep disorders and as feed for animals.³⁵

³⁴ Corn. Engage the Chain. (2019, August 27). Retrieved April 24, 2022, from <https://engagethechain.org/corn>

³⁵ Yakoot, M., Helmy, S., & Fawal, K. (2011). *Pilot study of the efficacy and safety of lettuce seed oil in patients with sleep disorders*. International journal of general medicine. Retrieved April 24, 2022, from <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3119588/>



How CEA Shapes the Future

Predicting the timeframe within which CEA will overtake various crops is variable based on how much value the space creates early on. With the aggressive assumptions that automation and renewable energy sources reduce variable labor costs to near zero, and that gene-editing and optimization for hydroponics allows any plant to be grown in a controlled environment, the interesting examination then becomes the relationship between the development of CEA and society as we know it today. To this examination I have three main questions:

1. If produce can be grown anywhere, what happens to products who currently derive much of their value from the location they're grown?

Consider grapes, a fruit that I could imagine transitioning to CEA in the next 20 years. As research develops on what attributes of soil and environment contribute to the hints of blackberry and plum in an Argentine Malbec or notes of pear and guava from a French Chardonnay, those conditions will become emulatable by CEA farms anywhere in the world. I'm not sure there'd be much demand for hydroponic wine, as the novelty and technological integration in the process seems antithetical to the values I perceive wine connoisseurs to have, but I digress.

In fact, many elements of terroir, including soil, climate, and altitude will become controllable parameters for a CEA farm.³⁶ The indoor farm could even use targeted lights to replicate the direction a vineyard faces. With a controlled system that can replicate every aspect of agriculture, the remaining bits of terroir would come solely from the actions of a winemaker.

³⁶ McIntyre, D. (2021, May 27). *How vineyard soils affect the taste of your wine*. The Washington Post. Retrieved April 24, 2022, from <https://www.washingtonpost.com/food/2021/05/28/soil-effects-on-wine-taste/>

What happens when the connection between food and place is dissolved? What happens to the culture, traditions, and stories wrapped up in local food, as we understand it today?

On a related note, CEA companies often boast the fact that their produce is local, and given the proximity of agriculture to consumption is indeed close, it is locally grown. How does this differ from *local food*, a concept that inherently belongs to a particular area or community? Similarly, many CEA operations meet organic certification requirements. Further, high startup costs, complexity, and economies of scale lends CEA to developing into a very centralized space. Supporting ‘local’ and buying ‘organic’ might begin to confuse consumers who want to support the small-plot romantic *cultivation* of agriculture. Should CEA be allowed to crop up in farmers markets? What happens if the taste of hydroponics becomes *too good*? Sounds like a sweet problem to have, but it would worry me to grow too accustomed to something that relies so much on technology.

2. If quality produce is cheap and plentiful, will we lose respect for it?

Although the abundance of goods should not affect the level of value we prescribe them, humans show time and time again that it does. This could explain the correlation between consumer food waste and per-capita GDP.^{37,38} For thousands of years, food has carried with it an air of spirituality, one which I believe has been eroded in parts of the world where food has become more abundant.

I worry that low costs for fresh, quality produce could contribute to a disregard for waste and a further removal between humans, cultivation, and nature. Without human involvement in the cultivation process, I fear that any respect derived from that process will be lost. Perhaps

³⁷ Barrera, E. L., & Hertel, T. (2020, March 13). *Global food waste across the income spectrum: Implications for food prices, production and resource use*. Food Policy. Retrieved April 24, 2022, from <https://www.sciencedirect.com/science/article/pii/S0306919220300762>

³⁸ Xue, L. (n.d.). *Correlation between per-capita GDP and per-capita consumer food waste*. Retrieved April 24, 2022, from https://researchgate.net/figure/Correlation-between-per-capita-GDP-and-per-capita-consumer-food-waste-a-households-R_fig6_316864687

there could be compelling stories told from machines, or from those farm workers who work with machines, but my lack of familiarity with such stories makes me think otherwise.

That said, I'm not sure how far we have to fall in this respect. I imagine a relatively small portion of America is exposed to the firsthand stories of industrial farmers, and I don't foresee CEA replacing subsistence or small-plot boutique farming.

3. Will the mechanization of cultivation necessarily further remove humans from nature?

Although most consumers are entirely removed from the agriculture behind the food they consume, there's something unsettling about the idea of robot-filled towers churning out produce. Unsettling as it may be, AI already plays a massive role in agriculture and I doubt that the end consumer, already entirely removed from the process, would notice or care much about the final severing of human interaction with the produce—rather that their produce has gotten a bit cheaper and fresher.

For the farmers of our society, however, I worry about the transition from traditional agriculture, however removed it may already be from society and from yeoman ideals, to an industry dominated by tech. Darin Kelly, a farmer from Indiana transitioned some of his operations to hydroponic agriculture with the goals of growing year-round, remarked about the growing method: "hydroponics is technical, and not simple. You've got to worry about plumbing, slope, pressure, and measuring nutrients. You become a plumber, you become an electrician."³⁹

As farms become increasingly technical, farming teams will increasingly be made up of data scientists, software engineers, designers, and business folk. This 'white colorization' of farming will likely bring about a variety of subtle shifts, many of which lend themselves to human alienation from the natural world.

³⁹ Hughes, A. J. (n.d.). *Experts: Hydroponic growing offers advantages, but won't replace soil*. Seedstock. Retrieved April 24, 2022, from <http://seedstock.com/2016/03/15/experts-hydroponic-growing-offers-advantages-but-wont-replace-soil/>

AI systems and machine learning models rely on ‘flattened’ data, created by converting what is observable by humans into numbers that machines can work with. A 2021 article titled *Managing the risks of artificial intelligence in agriculture* summarized my concerns with this eloquently: “The world is not data and plants and animals are not machines. Coming to treat the natural world as a data system to be analyzed and manipulated may be bad for us, intellectually and spiritually, and also bad for that world.”⁴⁰



The Yeoman Strikes Back

That isn't to say our relationship with nature is doomed; many large-scale hydroponics farms are putting roots down around urban centers, and I foresee those farms developing into community hubs with tours and tastings of produce and by-products created all on site. For decades, urban hubs have developed in the absence of agriculture and I believe the reuniting of the two will provide cities a much needed reconnection with nature, however artificial.

Outside the industrial scale, hydroponics startups such as Click and Grow and Smallhold are bringing agriculture into restaurants, home kitchens, and grocery stores. Such spaces have developed into independent stops along food's journey from farm to table, and I believe people will embrace the reappearance of agriculture adjacent to the preparation and consumption of food. These types of small scale CEA and hydroponic towers have found patrons from entities including the Chicago O'Hare International Airport and Wholefoods. Whether these small systems prove to become a new household staple or just a fad will depend on their ability to introduce real value to the lives of their customers. They address an opportunity to reconnect the next generation with their agriculture.

⁴⁰ Sparrow, R. (n.d.). *Managing the risks of Artificial Intelligence in agriculture*. Taylor & Francis. Retrieved April 24, 2022, from <https://www.tandfonline.com/doi/full/10.1080/27685241.2021.2008777>



Hydroponic towers in Chicago O'Hare International Airport⁴¹



Smallhold farm in Whole Foods supermarket in New Jersey⁴²

I see potential in a HelloFresh type subscription model, where consumers receive seeds every week or so to plant with a recipe for a meal three weeks down the line. The customer

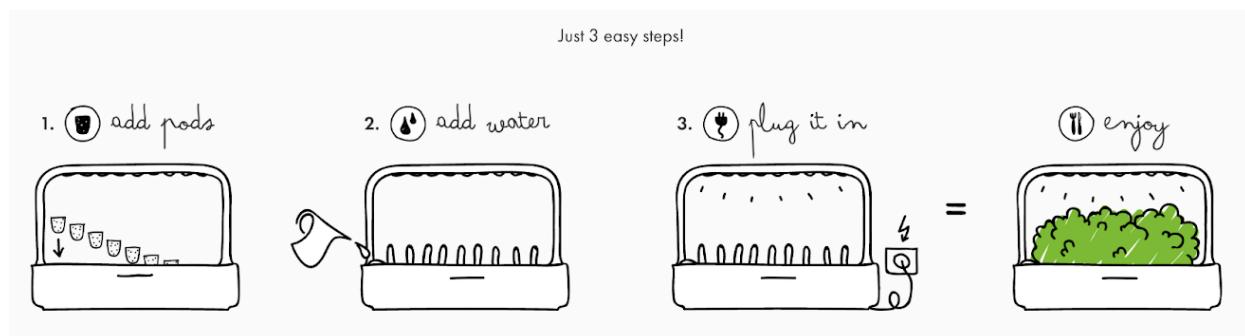
⁴¹ *O'hare Airport Urban Garden - indoor farming with Tower Farms.* Tower Farms. (n.d.). Retrieved April 24, 2022, from <https://www.towerfarms.com/us/en/possibilities/indoor-farming/chicago-ohare-airport>

⁴² Dawson, G. (2018, March 26). *New Whole Foods cultivates mini mushroom farm in produce section.* Supermarket News. Retrieved April 24, 2022, from <https://www.supermarketnews.com/produce-floral/new-whole-foods-cultivates-mini-mushroom-farm-produce-section>

could either pick up the necessary ingredients or opt in for the company to ship them around harvest time. Either way, consumers are afforded the pleasure of planting their crops, watching them grow, and enjoying them in a fresh meal. Properly done, I can see a model like this capitalizing on the same pride felt after cooking a HelloFresh meal: the company provides almost everything and chooses a recipe that's easy enough to do right but hard enough to give you the feeling that you worked for it, you earned it.

One doesn't feel like a chef heating up a frozen TV dinner, but one can feel like a chef when cooking HelloFresh. Finding the level of involvement that makes people feel like self-sufficient farmers is imperative, and I believe that feeling like a farmer would translate into a society with more empathy and care for our environment.

A business model like this would target upper and middle class consumers first, but I imagine many other ideas that could help make CEA a kitchen staple. Companies like Click and Grow present a potential paradigm shift of what makes up a kitchen, bringing fresh produce into every home.



How the Click and Grow system works, as per their website⁴³

What would this mean for Thomas Jefferson's agrarian hopes? I imagine he envisioned a bit more toil in the process, but would a system like this be a step in the right direction? Do those philosophies rely on self-sustainability or rather the toil and labor? Which creates the connection

⁴³ Indoor Herb Gardens and indoor gardening kits. Click & Grow. (n.d.). Retrieved April 24, 2022, from <https://www.clickandgrow.com/>

with nature? Is that the goal? I struggle to see a society in which we all return to the yeoman ways, but I can imagine a CEA farm in every kitchen.

If organic small plot farming is the means by which to understand the yeomen philosophies of honesty, virtue, hard work, and independence through agriculture, perhaps CEA can serve as a metaphorical religion to fast-track those learnings to the general populace.

The winds of innovation are blowing in favor of controlled environment agriculture, and I am inclined to believe the innovation won't stop at lettuce and tomatoes. The current burden on outdoor agriculture is too water dependent, inefficient with land use, and destructive to our soil. Capitalism isn't known to pay much respect to negative externalities, but as research and innovation drives down the costs of CEA and access to arable land and water continues to slim, the financial benefits of producing with CEA will overtake more and more traditionally grown crops.

CEA exists independent of our environment, liberating the resources of croplands, water, and human time for whatever else we choose to do. I have concerns given humanity's track record of increasing waste with affluence, as well as our digitization of nature, but I'm excited at the opportunity for CEA and hydroponics to rekindle a relationship between our society and agriculture.